GIS BASED ASSESSMENT OF SEISMIC RISK FOR THE CHRISTCHURCH CBD AND MOUNT PLEASANT, NEW ZEALAND

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ABSTRACT

This research employs a deterministic seismic risk assessment methodology to assess the potential damage and loss at meshblock level in the Christchurch CBD and Mount Pleasant primarily due to building damage caused by earthquake ground shaking. Expected losses in terms of dollar value and casualties are calculated for two earthquake scenarios.

Findings are based on: (1) data describing the earthquake ground shaking and microzonation effects; (2) an inventory of buildings by value, floor area, replacement value, occupancy and age; (3) damage ratios defining the performance of buildings as a function of earthquake intensity; (4) daytime and night-time population distribution data and (5) casualty functions defining casualty risk as a function of building damage. A GIS serves as a platform for collecting, storing and analyzing the original and the derived data. It also allows for easy display of input and output data, providing a critical functionality for communication of outcomes.

The results of this study suggest that economic losses due to building damage in the Christchurch CBD and Mount Pleasant will possibly be in the order of \$5.6 and \$35.3 million in a magnitude 8.0 Alpine fault earthquake and a magnitude 7.0 Ashley fault earthquake respectively. Damage to non-residential buildings constitutes the vast majority of the economic loss. Casualty numbers are expected to be between 0 and 10.

ACKNOWLEDGMENTS

I owe great debt of gratitude to Jim Cousins of GNS Science, whose works I have drawn upon and for his guidance during some of the most critical stages of this research. Special thanks are owed to my parents and my husband for their personal support and encouragement. I would also like to thank several other people, in particular: Dave Heron (GNS Science) for providing me with digital geological data and masses of extremely useful literature and references at the outset; Jarg Pettinga (Canterbury University) and Mark Rattenbury (GNS Science) upon whose suggestion I chose this topic and began this thesis; Steve Bensberg (Christchurch City Council) for providing several data sets and John Taylor (Christchurch City Council) for helping me with a number of enquiries relating to building data. And last but by no means least, I am grateful to my supervisors, Clive Sabel, Ian Owens and Tim Davies for their careful proof reading and guidance with the structure of this thesis and for their willingness to take on a student working mostly off campus.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Throughout history, earthquakes have been responsible for significant numbers of casualties and billions of dollars of damage to structures. The continued probability for the occurrence of large earthquakes, together with a growing population, increases the seismic risk in many communities. Seismic risk cannot be eliminated, but it can be effectively analysed and possibly reduced by using proper tools and models for combining information to produce reliable and meaningful estimates of the seismic risk facing a community. A seismic risk assessment can be applied to help urban planners, emergency managers, risk managers and public policy/decision makers understand the impact of earthquakes, study the effect of mitigation techniques and incorporate the results into preparedness programs and urban development plans.

In urban centres, the seismic risk is best quantified and portrayed through the preparation of earthquake damage and loss scenarios. The components of such scenarios are the assessment of the seismic hazard, inventories and vulnerabilities of elements at risk. Modern methods for assessing seismic risk include the use of Geographic Information System (GIS) technology. A GIS creates new opportunities for managing the large amount of data, for interfacing with external analysis programs and for presenting the results in a manner that can be useful for disaster planning, hazard and risk mitigation.

New Zealand's Resource Management Act (RMA) 1991 and the Civil Defence Emergency Act 2002, require local authorities to identify, assess and mitigate the effects of natural hazards and other technological hazards. Several seismic hazard assessment studies for Christchurch and the Canterbury region (Elder *et al.*, 1991b; Berrill *et al.*, 1993; Dowrick, 1998; Yetton *et al.*, 1998; Stirling *et al.*, 2001) indicate that potential exists for relatively rare but very large earthquakes (approximately magnitude 8.0) along the Alpine fault. More frequent moderate to large earthquakes (around magnitude 6.0-7.5) can be expected in the Canterbury Plains foothills and North Canterbury area, and less frequent moderate earthquakes under the Canterbury Plains and Christchurch itself.

Damage assessment is a vital ingredient in developing environmental policies designed to meet the requirements of the RMA (Aggett, 1994). Over the years several seismic risk assessment studies (Elder *et al.*, 1991; Cousins, 2005a; Christchurch Engineering Lifelines Group,1997; Institute of Geological and Nuclear Sciences (IGNS), 1994; Soils and Foundations, 1999) have been carried out for Christchurch and each have considered some aspects of damage and loss to the city but have been greatly limited in their ability to produce geographically detailed results.

This study uses GIS technology to assess seismic risk for the Christchurch CBD and Mount Pleasant (Figure 1.1) due to two earthquake scenarios. Findings are based on: (1) data describing the earthquake ground shaking and microzonation effects; (2) an inventory of buildings by floor area, replacement value and occupancy; (3) damage ratios defining the performance of buildings as a function of earthquake intensity; (4)

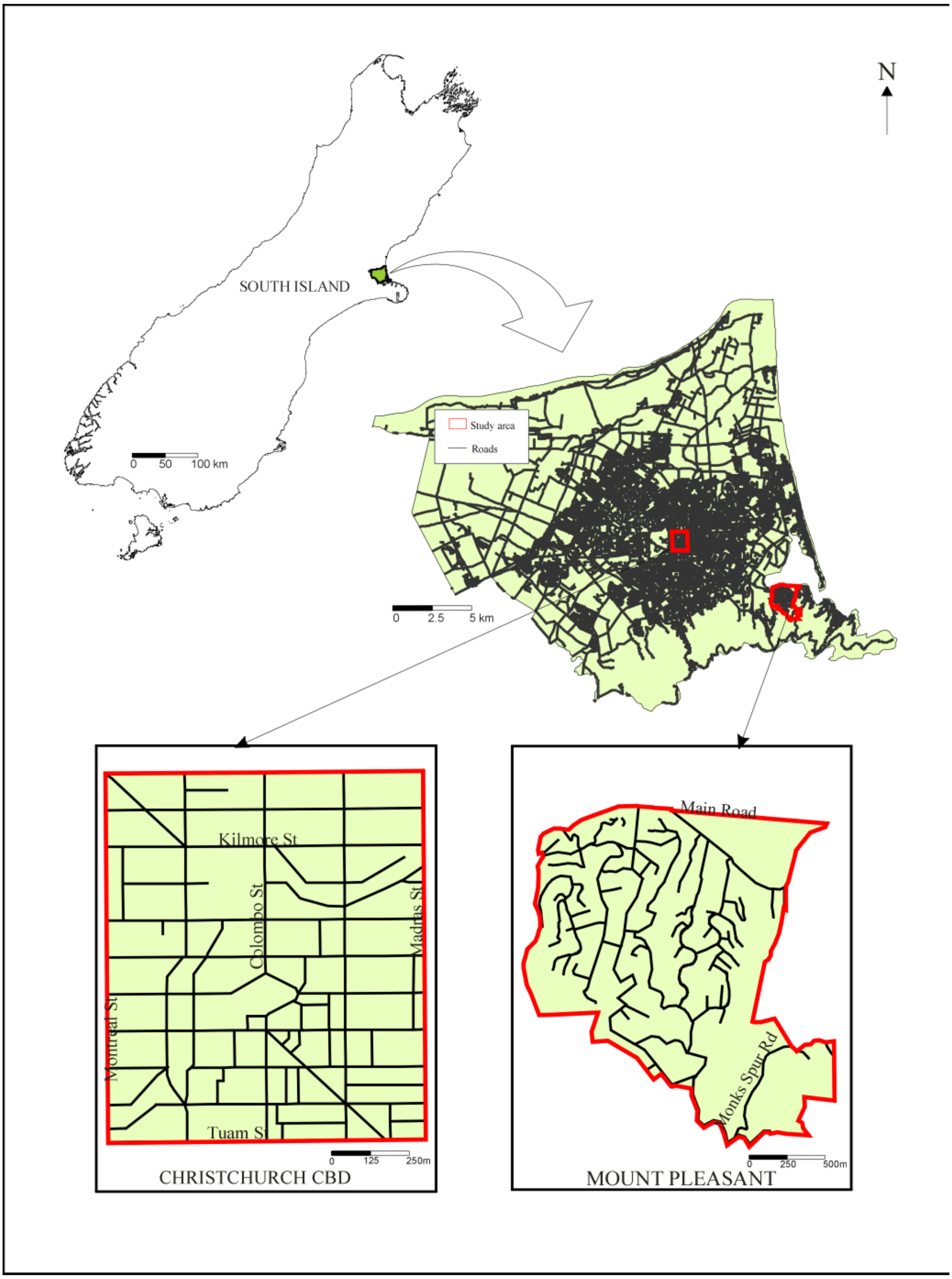

Figure 1.1 Locality Map.

daytime and night-time population distribution data and (5) casualty functions defining casualty risk as a function of building damage. By utilizing GIS technology, this research attempts to improve upon our understanding of the geographic variation of seismic risk in Christchurch due to building damage caused by earthquake ground shaking. A GIS not only provides the analytical "engine" for the risk assessment, it also provides a potent form of risk communication through its capacity to provide a visual representation of the spatial distribution of seismic risk in the city.

It is important to note that this seismic risk assessment study assesses damage and loss at meshblock level and is not designed at site-specific level. The results therefore are not intended to predict the expected damage and loss at a specific site or for a specific building and should not be used for such purposes.

1.2 AIMS

The principal aim of this research is to use a deterministic seismic risk assessment methodology to assess building damage and casualty risk primarily due to earthquake ground shaking in the Christchurch CBD and Mount Pleasant in two hypothetical seismic events: (1) a magnitude 8.0 earthquake on the Alpine fault, at a distance of 130km from Christchurch, which produces shaking intensities of near MM7 in the city and (2) a magnitude 7.0 earthquake on the Ashley fault, at a distance of 25 km from Christchurch that produces shaking intensities of near MM8 in the city.

1.3 OBJECTIVES

Major objectives of this research are as follows:

- Estimate building damage in terms of dollar value in the Christchurch CBD and Mount Pleasant due to ground shaking in two specified earthquake scenarios; and
- Estimate casualties in the Christchurch CBD and Mount Pleasant, arising solely from the collapse of buildings in two specified earthquake scenarios.

1.4 THESIS ORGANISATION

This thesis comprises eight chapters:

- Chapter 1 briefly introduces the seismic risk problem and explains why it is necessary to conduct seismic risk assessments. It concludes with a summary of the primary aim of this study.
- Chapter 2 provides a description of the major components of a seismic risk assessment methodology. GIS is introduced and the process of conducting a seismic risk assessment in the geographic information system environment is described.
- Chapter 3 describes the tectonic setting of Christchurch in the context of New Zealand. It then outlines the geological and seismological aspects of the seismic hazards existing in the city and concludes with a description of the buildings and population at risk.
- Chapter 4 gives an overview of the seismic hazard model. The attenuation model and the effects of microzonation are also described.
- Chapter 5 presents the methodology of building inventory compilation. It

also gives a description of the methodology used to determine the distribution of population in the study areas, in different building types, and for different times of the day.

- Chapter 6 gives a background and overview of damage forecasting, including derivation of damage ratios, which relate the earthquake ground shaking in terms of the Modified Mercalli Intensity (MMI) scale to a given building construction class. The economic loss and casualty models are described.
- Chapter 7 presents the damage and loss estimation results. Results are presented in tabular and graphic form. The spatial patterns of economic loss estimates are identified.
- Chapter 8 presents a summary of the main findings of this study. The sources of uncertainty in seismic risk assessment studies are also discussed followed by recommendations for future research.

CHAPTER 2

SEISMIC RISK ASSESSMENT AND GEOGRAPHIC INFORMATION SYSTEMS

2.1 INTRODUCTION

The goal of seismic risk assessment is to quantify the potential damages and losses in a region due to future earthquakes (King & Kiremidjian, 1994). A seismic risk assessment requires the synthesis of data and the essential mapping of the spatial relationships between the seismic hazard and the elements at risk. A geographic information system (GIS) is mapping software that provides an ideal environment to accomplish the objectives of a seismic risk assessment study because it has the ability to store, manipulate, analyse and display the large amounts of spatial and non-spatial information needed for a seismic risk study. This chapter begins with a description of the major components of a seismic risk assessment, followed by a broad overview of GIS and concludes with a explanation of how seismic risk assessment is conducted in the geographic information system environment.

2.2 SEISMIC RISK

In studies done over the years, many specialists have used the terms seismic risk and seismic hazard synonymously, although it is now well recognised that there is a difference between these two terms. Seismic hazard describes the potential for dangerous, earthquake-related natural phenomena such as ground shaking or fault rupture. These phenomena could result in adverse consequences to society such as the destruction of buildings or the loss of life (Reiter, 1990). On the other hand, seismic risk is defined as the probability of losses directly or indirectly provoked by earthquakes. These are losses that might be suffered by the population or by the built environment as well as by the economic system (Musson, 2000). Risk can thus be seen as the interaction between a seismic hazard phenomenon, the elements that are exposed to that hazard, such as people, houses and so on, and the degree to which those elements are more or less vulnerable to the impact (Granger & Hayne, 2001). Therefore, while seismic hazard is purely a product of natural processes, seismic risk is dependent on societal exposure. The relationship between seismic hazard, risk and vulnerability can be written in terms of a simple equation where,

Seismic Risk = Seismic Hazard x Elements at Risk x Vulnerability of elements at risk (modified after Musson, 2000).

Where,

"Hazard" is the probability of occurrence, within the specified period of time in a given area, of a potentially damaging natural phenomenon, in this case, an earthquake.

"Elements at Risk" is defined as the population, buildings, economic activities, public services, utilities and infrastructure, etc., at risk in a given area.

"*Vulnerability"* is defined as the degree of loss to a given element at risk or set of such elements resulting from the occurrence of an earthquake of a given magnitude.

In terms of the definitions given above, there have been many studies of seismic hazard but relatively few of seismic risk (Musson, 2000).

2.3 COMPONENTS OF A SEISMIC RISK ASSESSMENT STUDY

A seismic risk assessment study comprises several components as shown in Figure 2.1. Seismic risk is a product of seismic hazard and its consequences (Reiter, 1990). Hence, the assessment of seismic hazard is the first step in the evaluation of seismic risk. The potential seismic hazards that will affect Christchurch following a seismic event are discussed in Chapter 3.

2.3.1 SEISMIC HAZARD

The purpose of assessing earthquake hazards is to identify and quantify the severity of the various hazards in the geographic area of interest (Federal Emergency Management Agency (FEMA), 1989). Three key models are typically used in order to calculate the seismic hazard in an area. These include:

1) Seismic source and occurrence models, which include the definition of each source's geometry and earthquake potential;
2) An attenuation model, which describes generally how earthquake ground shaking or intensity decreases with distance away from the earthquake source; and
3) A site response model, which describes how local soils, geological sediments weathered rock and topography will affect the ground shaking experienced during the earthquake (Elder *et al.*, 1991b).

Peek-Asa *et al*. (2000) report that the primary and most pervasive hazard associated with earthquake is the shaking of the ground. According to theoretical models of earthquake damage, ground shaking activity initiates a cascade of events. In this cascade, ground motion which begins and dissipates from the epicentre, correlates with building and contents damage which consequently results in casualties. For this reason, the primary aim of this research is the estimation of damage to the building stock due to earthquake ground shaking. Hence, the discussions that follow focus on modelling building damage due to earthquake ground shaking and quantifying loss in terms of dollar value and casualties. This study does not include losses due to damage to lifeline components because the technique for lifeline loss estimation was seen to be too time-consuming to be incorporated and a relatively recent lifelines study has been undertaken for Christchurch by the Christchurch Engineering Lifelines Group (1997).

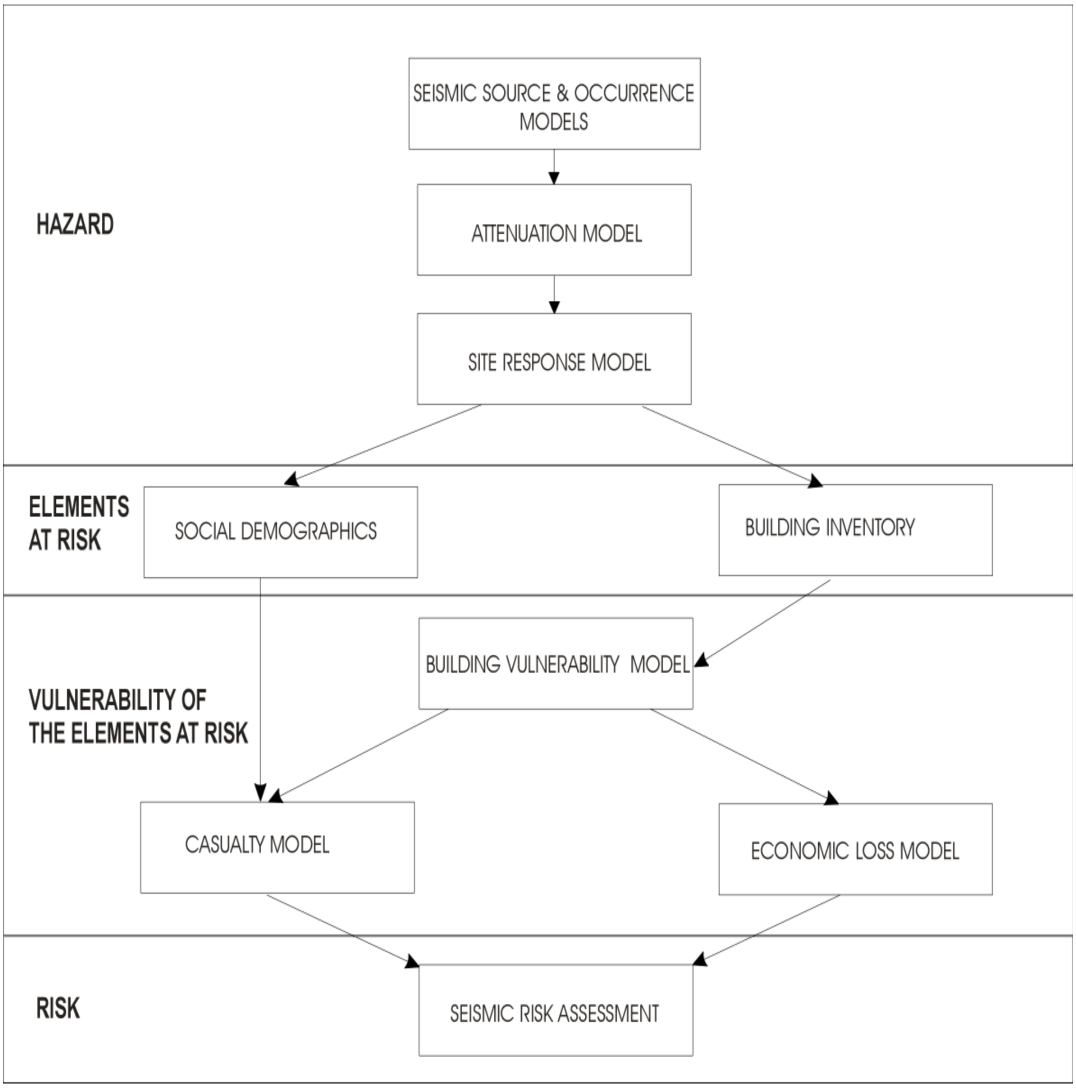

Figure 2.1 Components of a typical seismic risk assessment study (modified after Fulford *et al.*, 2002).

2.3.2 ELEMENTS AT RISK

INVENTORY DATA

Once the seismic hazard and local site effects have been sufficiently characterised, the next step is the compilation of inventory databases. Inventory (or exposure) databases provide information on the built environment including building stock, transportation system, lifeline (utilities) system and critical facilities (Bendimerad, 2001) and hence, generally describe the physical, financial and social exposure to earthquake loss (Davey, 1994). Classification systems are used to categorise exposures into groups of similar risk characteristics. Such characterisations are then related to vulnerability functions. Vulnerability functions are discussed in section 2.3.3. Furthermore, the development of an accurate and complete inventory of a certain type of exposure for a region, is the most important and often the most time-consuming and costly step in a seismic risk assessment study. Thus, the inventory task is often a matter of using the data that can be collected and organised within the time and budget allotted, rather than developing the perfect inventory (FEMA, 1989). It is important to note, however, that the accuracy of the final damage and loss estimates is highly dependent upon the accuracy of the underlying inventory developed for an area.

In Christchurch, most major lifeline facilities are already inventoried to some extent (Christchurch Engineering Lifelines Group,1997). It is the more difficult problem of conducting an inventory of buildings classified by occupancy (residential, industrial, and commercial) and by building type (structural system and material, height) that is the focus of this research. Most New Zealand studies have used either proprietary (insurance portfolio) or Valuation New Zealand (VNZ) building data to compile building inventories for seismic risk assessment studies (Davey, 1994). Census data from the Department of Statistics is typically used to determine the distribution of population within a study area. The methodology of compiling a building inventory and the mapping of population distribution within the study area is thoroughly discussed in Chapter 5.

2.3.3 BUILDING VULNERABILITY MODEL

Although in actual practice, the steps in a seismic risk assessment study do not necessarily proceed sequentially, the earlier discussed tasks of seismic hazard analysis and inventory are theoretically the two steps that come before the process of relating the ground motion to a given building construction class to estimate damage (FEMA, 1989).

Earthquake damage is associated with direct consequences (damage to property or loss of function) and indirect consequences (such as loss of productivity or jobs) (McGuire, 2004). Direct damage due to earthquakes can be expressed in a variety of ways. Different authors use different terms and parameters to express earthquake damage. Two of the most commonly used terms are (1) damage index and (2) damage ratio. The term “damage index” is taken to mean the characterisation of individual element (local) or entire structure (global) damage based on response parameters such as ductility ratio (FEMA, 1989). King and Kiremidjian (1994) report that these indices are generally too structure specific to be considered for regional damage description. The term “damage ratio" is defined by several authors (Dowrick, 2003; Cousins, 2004, 2005a) as the cost of damage to a building divided by the replacement value of the building, where ground shaking is characterised by the Modified Mercalli Intensity (MMI). This can be expressed as:

$$\textbf{Damage Ratio } (\mathbf{D_r}) = \frac{\textbf{Cost of damage to building}}{\textbf{Replacement value of building}}$$

The damage ratio or the mean damage ratio for groups of similarly affected structures can be estimated for the effects of ground shaking as described below.

Direct physical building damage resulting from earthquake ground shaking is usually estimated through the use of motion-damage relationships, which are also known as vulnerability functions (Rojahn, 1994). Identifying the relationship between the intensity of ground shaking and the damage experienced by a group of generally similar structures or building construction class is essential to vulnerability analyses (Finn, 1994).

Motion-damage relationships can be expressed in several ways. In this study, the relationship between ground shaking and damage is expressed using damage-loss curves. This is reported (FEMA, 1989) to be the most common method for representing the relationship between ground shaking and damage. The relationships were developed by Algermissen and Steinbrugge (1984) and they indicate the average loss, measured as a percentage of total value of the building inventory as a function of ground shaking intensity, where ground motion is characterised by Modified Mercalli intensity (MMI) (Dowrick, 1991).

The use of damage ratios and the MMI for motion-damage relationships is standard practice in the USA and New Zealand (Davey, 1994). An in-depth description of damage modelling as applied to this study is given in Chapter 6 of this thesis.

Other ways of expressing motion-damage relationships are through the use of (1) Fragility Curves and (2) Damage Probability Matrices. Fragility Curves describe the probability that a specified damage level will be exceeded for a given intensity of ground motion. Damage Probability Matrices describe the probability that a structure is in a specified damage state given the level of ground shaking intensity (Ventura *et al.*, 2005). King and Kiremidjian (1994) state that there is no difference in the information that is conveyed or can be obtained through the use of fragility curves and damage probability matrices. Thus, the choice is a matter of style and precedent.

2.3.4 LOSS MODEL

The final step in a seismic risk assessment procedure is the estimation of losses based on damage distributions predicted in the previous step. To estimate losses from damage, the damage descriptors must be translated into economic loss or other quantitative units such as the number of people requiring hospitalisation (McGuire, 2004). Therefore loss is typically divided into two major classes: economic and non-economic loss.

1. ECONOMIC LOSSES

Economic losses resulting from an earthquake are typically due to (1) direct physical damage, such as failed beams and (2) indirect effects, such as loss of facility use for some finite time after an earthquake. In most cases, studies have defined direct physical damage in terms of repair and replacement costs of the building stock (Davey, 1994). The losses, however, may possibly be more extensive than just the direct physical impacts. As a result of an earthquake, business interruption, building contents loss, business inventory loss, relocation expenses and income losses may also occur. There may be ripple effects throughout the economy. Additionally, indirect economic losses may occur in economic sectors not sustaining direct damages (Brookshire *et al.*, 1997). Indirect economic losses are more difficult to quantify than direct economic losses. Attempts to estimate the indirect economic impacts can complicate the study procedures significantly, especially with respect to collecting additional information about structures and identifying the interrelationships among sectors in the economy and how they would change after a seismic event (FEMA, 1989).

2. NON-ECONOMIC LOSSES

Non-economic loss due to seismic activity typically depends on the characteristics of the regional population and can include effects such as fatalities, injuries, unemployment and homelessness (Davey & Sheppard, 1995). The most significant non-economic loss is that of death and serious injury. The continued probability for the occurrence of large earthquakes, coupled with a growing population, increases the risk for earthquake-related casualties (Peek-Asa *et al.*, 2000). One of the earliest studies relating seismic hazard and building damage to risk of injury was carried out by Algermissen et al. (1972). Its treatment of casualty estimation provided the foundation for later studies (Davey, 1994). This report focuses heavily on injuries, casualties, and availability of medical supplies and services. More recent epidemiological research examining risk factors for earthquake-related injury focuses on the dynamics occurring throughout the event, from pre-disaster preparedness to post-disaster response and recovery (Peek-Asa *et al.*, 2000). In the 1980s quite a few studies predicting casualties due to building damage were done by the Federal Emergency Management Agency/National Institute of Building Sciences (FEMA, 1989; Davey, 1994; Kircher *et al.*, 1997; Whitman *et al.*, 1997). Furthermore, several studies (Davey & Sheppard, 1995; Spence *et al.*, 1998; Cousins & Heron, 2000; Cousins, 2004, 2005a) predicting casualties due to building damage have also been done for New Zealand.

Models for non-economic earthquake losses have not been fully developed as these effects depend on several factors that are difficult to quantify. In addition, earthquake-related casualty models are developed from expert opinion based on very sparse data. Hence, estimates of casualties are often crude and uncertain, and this uncertainty should be represented by giving ranges of estimates (FEMA, 1989).

The focus of this study is to estimate economic loss primarily due to direct damage to buildings, where damage is expressed as a percentage of replacement value. The only non-economic loss that is estimated is casualties due to building damage.

2.4 GEOGRAPHIC INFORMATION SYSTEM TECHNOLOGY

In this seismic risk assessment study, GIS technology is utilised. There are many definitions for a GIS and there are contradicting views as to what are the necessary components and capabilities of a true GIS. The most universal definition in the literature for a GIS is “A system of computer hardware, software, and procedures designed to support the capture, management, manipulation, analysis, modelling and display of spatially referenced data for solving complex planning and management problems” (Demers, 1999).

2.4.1 GIS DATA STRUCTURES

Geographic data comes in three basic forms:

1) **Map data -** map data contains the location and shape of geographic features and are known as spatial data. A GIS uses three basic shapes to present real-world features: points, lines, and polygons.

2) **Attribute data -** attribute (tabular) data is the descriptive data that GIS links to map features. Attribute data is collected and compiled for specific areas like territorial authorities, census tracts, cities, and so on.

3) **Image data -** image data ranges from satellite images and aerial photographs to scanned maps.

Spatial information that is used in the risk assessment process, which includes fault locations, seismicity, geology, building stock, population, etc can be represented in a

GIS as features and their associated attributes. The features are represented by the basic data structures of the GIS, which are points, lines and polygons and the associated attributes are stored in database tables.

2.4.2 ANALYSIS AND MODELLING CAPABILITIES

One of the most important features of GIS is the manipulation and analysis of both spatial and non-spatial data. Both traditional database management systems and GIS support database analysis, but a GIS also supports map analysis. It is useful to think of GIS map analysis in layered-model context (Figure 2.2). The layered GIS model is analogous to transparent maps that can be accurately stacked upon one another. Typically each layer contains only one mapped theme. A GIS provides a set of "tools" or computer programs that allow the user to perform a specific set of operations on map and attribute data. These tools, which are in the form of operating commands, permit spatial inquiry, manipulation and analysis.

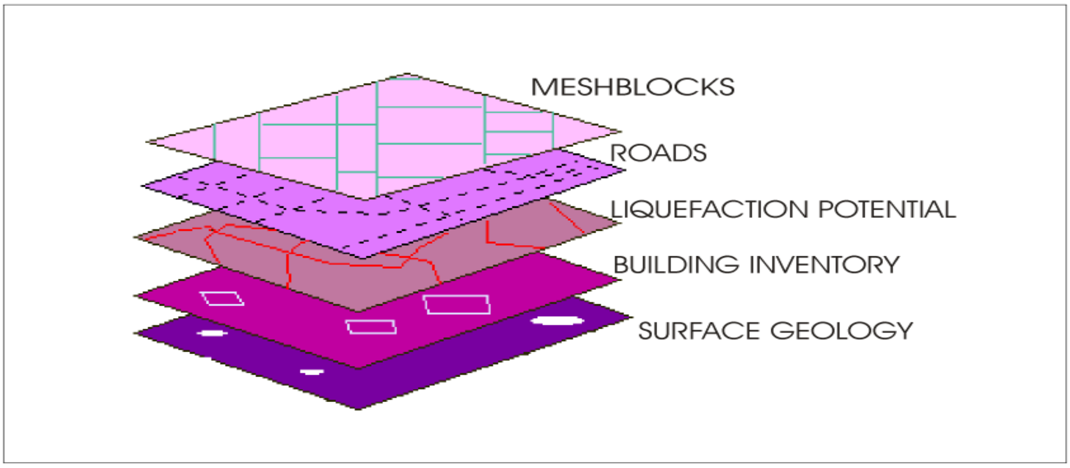

Figure 2.2 The layered GIS model.

2.5 APPLICATION OF GIS TECHNOLOGY TO SEISMIC RISK ASSESSMENT

Section 2.3 of this chapter gave a broad overview of seismic risk assessment and Section 2.4 gave a general description of GIS technology. This section explains how these two topics generally fit together.

As discussed in earlier sections, a seismic risk assessment process consists of seismic hazard assessment, vulnerability analysis and damage and loss modelling. Seismic hazard and risk are both location dependent. The probability of occurrence of earthquakes varies spatially and the vulnerability of buildings and population is dependent on their exposure to the hazard, which also varies spatially. The spatial characteristics of hazard and vulnerability justify the use of GIS technology (Lavakare & Krovvidi, 2001).

A geographic information system can be used to integrate the various steps in a seismic risk assessment process. The system is independent of analysis scale and geographic location, allowing analysis at any level and in any area where the necessary information is available. GIS technology also provides a powerful tool for displaying outputs and permits users to “see” the geographic distribution of risk (Bendimerad, 2001; Rasheed & Weeks, 2003).

The following sections and Figure 2.3 illustrate how a GIS works to combine the separate components needed for seismic risk assessment.

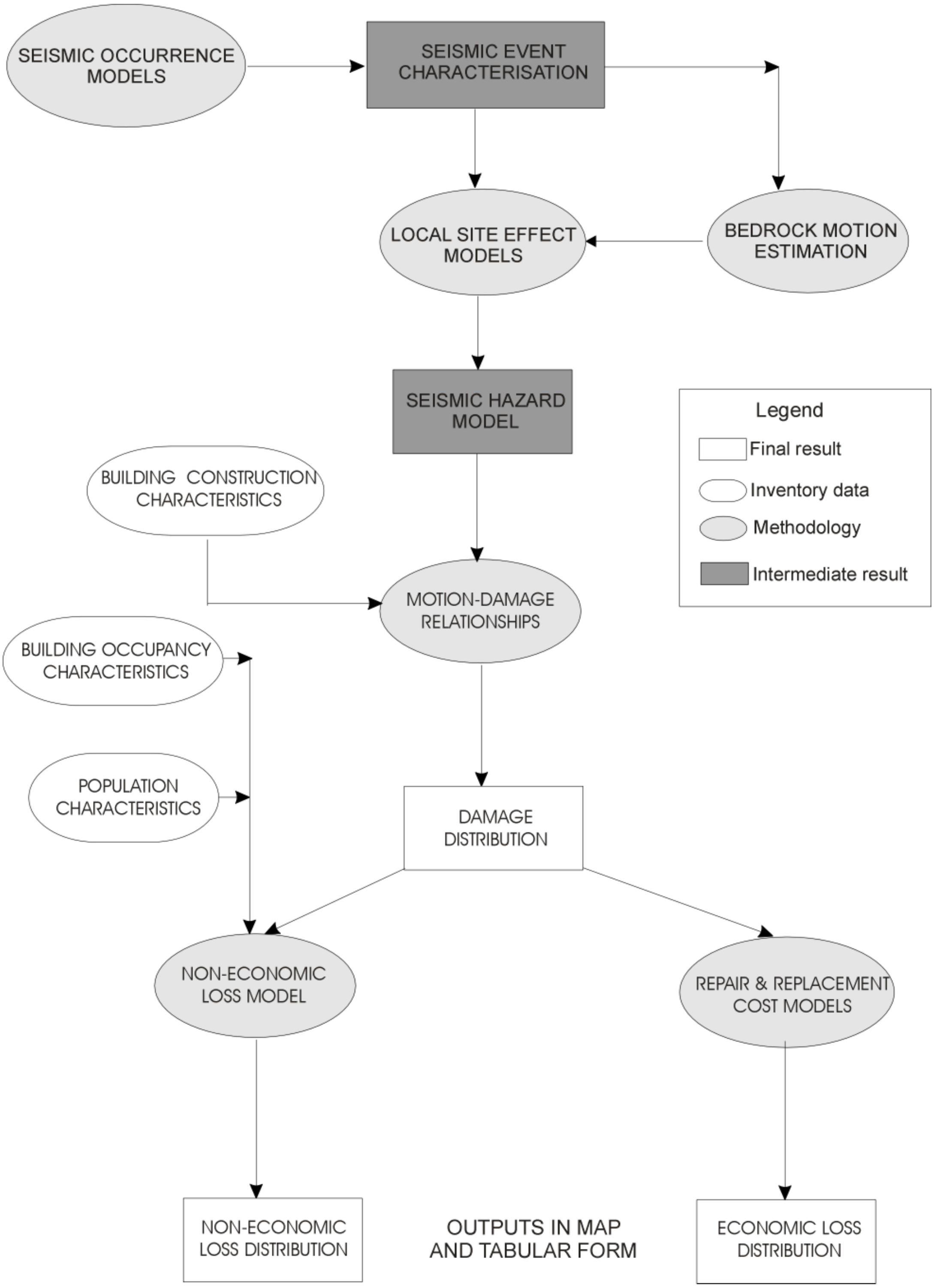

Figure 2.3 Flowchart showing the basic procedure for a GIS-based seismic risk assessment (modified after King & Kiremidjian, 1994)

2.5.1 SEISMIC HAZARD MODEL

The first step requires a map of the region that identifies the potential seismic sources. A source is selected and an occurrence model is applied either by implementing the model within the GIS or by linking it as an external executable program. Another method for determining the characteristics of a seismic event is to assume a scenario earthquake occurring on a given source. Application of such a model allows the user to construct a hypothetical situation and forecast the outcome. This is known as deterministic modelling and is discussed in further detail in Chapter 4 of this thesis. Database tables of seismic activity in the region are often used to aid in the occurrence modelling procedure and in the assumption of a historical scenario earthquake. Second, the bedrock motion resulting from the seismic event must be determined. This is done by applying an attenuation function within the GIS or by linking the function as an external executable program. These procedures normally require quite a few geologic and geographic maps of the study area. Then, the seismic hazard due to local site effects such as amplification and liquefaction has to be quantified. The process involves developing models for each of the effects, assembling the required geologic and geographic maps and databases, applying the models either within the GIS or as linked executable programs and the overlaying and combining the resulting hazard maps (King & Kiremidjian, 1994).

2.5.2 DAMAGE MODELLING

Building damage forecasting requires an inventory of buildings in the study area, a quantification of the seismic hazards, and equations that relate damage to hazard for each building class. The spatial database structure of a GIS environment is ideal for this procedure. Building inventory data can be stored without difficulty within the GIS database or in tables in an externally linked database management program. Relationships to estimate building damage are applied within the GIS, but can also be used through external program links. The general procedure involves combining maps of seismic hazard with maps of building locations according to set motion-damage relationships producing maps of damage distribution (King & Kiremidjian, 1994). Damage estimation leads to the knowledge/awareness of the extent of damage, which the study area will incur if an earthquake were to occur. It is possible to know not only the total amount of damage but also the weak points of the study area through the analysis. This information is very important to manage effective seismic disaster reduction measures, including preparedness, emergency response activities, and seismic retrofit and recovery actions and policies.

2.5.3 LOSS MODELLING

The final and most important result of a seismic risk assessment is the estimation of economic and non-economic loss distributions. As with damage forecasting, the GIS environment is ideal for estimating loss distributions. The process involves combining maps of damage distributions with maps and database tables of building and population inventories according to relationships defining loss as a function of damage (King & Kiremidjian, 1994). The final products are “risk surface maps” that illustrate the spatial relationship between levels of exposure and vulnerability.

There are several GIS-based seismic risk assessment modelling packages. A brief overview on three of these packages is given in Section 2.6.

2.6 SEISMIC RISK ASSESSMENT MODELLING PACKAGES

2.6.1 HAZUS

HAZUS (HAZard USa), which was initiated by the Federal Emergency Management Agency, is a software package that operates through MapInfo, a GIS application. This package combines transportation and utility lifeline losses with losses associated with the general building stock and essential facilities, e.g. hospitals. Extensive default databases for all American States containing information concerning the built infrastructure and demographics are included in the software. The modelling components address issues of damages due to direct seismic hazards and induced hazards. Economic losses, non-economic and social losses are calculated. Emergency response issues are also addressed. Long-term effects upon the regional economy can be evaluated in addition to immediate economic and social losses (Whitman *et al.*, 1997).

2.6.2 RADIUS

RADIUS (Risk Assessment tool for DIagnosis of Urban areas against Seismic disasters) is designed in MS Excel and freeware GIS (ESRI's ArcExplorer). It was developed through the support of UN-IDNDR (International Decade for Natural Disaster Reduction), to promote worldwide activities for reduction of seismic disasters in urban areas, particularly in developing countries. The damage and loss distributions are displayed as a mesh of rectangular cells. Outputs are seismic intensity, building damage, lifeline damage and casualties, which are presented in both tabular and map form (Lavakare & Krovvidi, 2001).

2.6.3 CITYAWARE

CityAware operates within ArcInfo, a GIS application. It was developed by the Geological and Nuclear Sciences (GNS Science) for the Wellington Emergency Management Office of the Wellington City Council. It is a computer tool for estimating and displaying the impact of earthquakes on the Wellington community. The model enables users to get estimates of casualties, numbers of homeless and the cost of building damage for each suburb for a wide range of earthquake scenarios. Users can edit copies of the underlying data to look at "what-if" scenarios that examine how changes to the city environment might reduce its vulnerability (Cousins *et al.*, 2000).

2.7 SUMMARY

There is a common theme to the seismic risk assessment process beginning with seismic hazards and inventory, leading to the calculation of direct and indirect physical damage, and concluding with the estimation of economic and social loss. The usual outputs of seismic risk assessments are estimations of one or a combination of direct social losses, direct economic losses and indirect economic losses. Furthermore, GIS technology is a powerful tool that can be used in seismic risk assessment as it provides an ideal framework for integrating the various components of a seismic risk assessment model and it also provides a powerful visual tool for displaying outputs and permits users to "see" the geographical distribution of risk.

CHAPTER 3

SEISMIC HAZARDS AND ELEMENTS AT RISK IN CHRISTCHURCH CITY

3.1 INTRODUCTION

This chapter begins with a description of the tectonic setting of Christchurch in the context of New Zealand. It then outlines the geological and seismological aspects of the seismic hazards existing in the city followed by a description of the buildings and population at risk.

3.2 TECTONIC SETTING OF THE REGION

New Zealand is susceptible to earthquakes because it lies across two of the earth's great tectonic plates – the Pacific plate in the east and the Australian plate in the west (Figure 3.1). To the east of the North Island, the Pacific plate is being subducted under the Australian plate. In the far south, subduction is occurring but in the opposite sense, with the Australian plate being subducted beneath the Pacific plate (Berrill *et al.*, 1993). Between these two opposing subduction systems, the zone of collision is too buoyant to subduct and the convergence, therefore, is accommodated by the landmass being twisted and torn by complex horizontal movement (faulting) and vertical movement (dominantly uplift) (Brown & Weeber, 1992). In the South Island, this collision is largely accommodated by the Alpine fault (Figure 3.1), at the western edge of the

Canterbury region (Stirling *et al.*, 2001). The city of Christchurch is located on the Canterbury Plains near the edge of this tectonically active region, with active faults to the north and northwest in Canterbury, and the Alpine fault to the west. There are twenty-six known active faults within 150 km of Christchurch City (Figure 3.1). The nearest known active faults are the onshore Ashley, Springbank and the offshore Pegasus Bay fault zones about 25km to the west and north of the city. The Alpine fault, located 130 km from Christchurch, is the largest active fault in New Zealand, and extends over 650km in length (Yetton *et al.*, 1998).

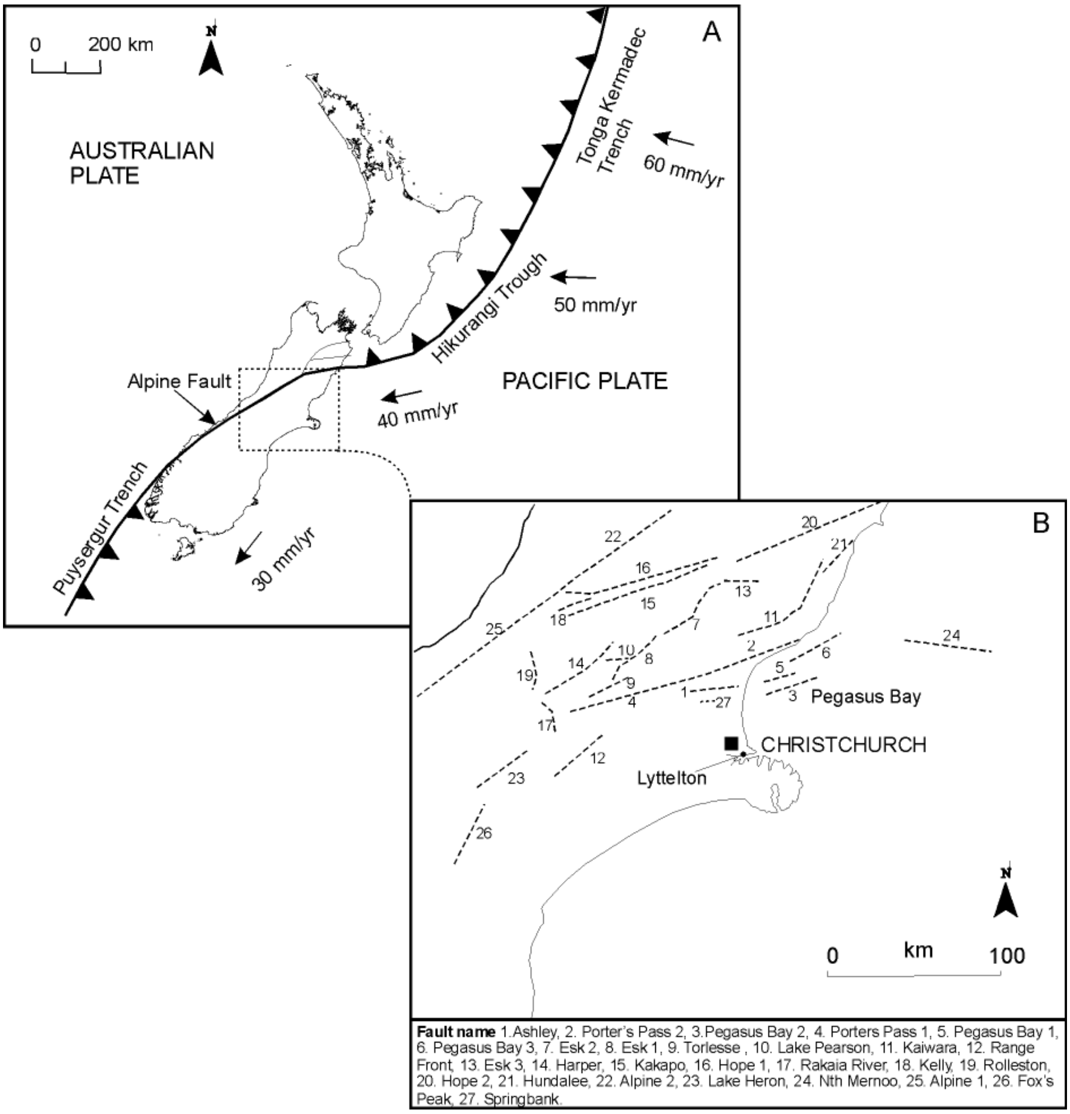

Figure 3.1 (A) Australian and Pacific plate boundary in New Zealand (modified after Reyners, 1998), (B) Active faults near Christchurch (modified after Dowrick *et al.*, 1998).

3.3 CHRISTCHURCH GEOLOGY

Christchurch City is located over geologically recent deposits of alluvial gravels laid down by the Waimakariri River, and fine marine sediments deposited on the coastal margin of the floodplain and in estuaries and lagoons. The sediments are about 700 metres deep, principally coarse-grained fluvial greywacke sands, gravels and silts, but with extensive sands in the eastern, seaward part of the city and with intermingled estuarine deposits especially in the central, south, and southeastern areas. The sediments lie on 200-300 metres of volcanic rock overlying greywacke basement at about 1000-metre depth (Berrill *et al.*, 1993). To the south of the city, the sediments become shallower against the weathered volcanic cone of Banks Peninsula. The Port Hills are mantled with loess soils over the basalt rock (Christchurch Engineering Lifelines Group,1997).

3.4 CHRISTCHURCH SEISMICITY

In the last 150 years, many earthquakes have been felt in Christchurch. The highest recorded levels of ground shaking of 7-8 on the Modified Mercalli intensity (MMI) scale (Appendix 1) were recorded in 1869. This was named the New Brighton Earthquake by Elder *et al.* (1991b) who suggest that it was of magnitude 5.75, with an epicentre 10 km from Christchurch city centre. Dibble *et al.* (1980) consider the New Brighton earthquake to be the most destructive since European settlement. Furthermore, Cowan *et al.* (1994) report an 1870 and an 1895 earthquake with epicenters in Southern Pegasus Bay, which resulted in strongly felt ground shaking in Christchurch. In 1888, a magnitude 7-7.3 earthquake in North Canterbury toppled the brick spire of the Christchurch Cathedral. Amplification of shaking induced by soft sediments and alluvium beneath the city resulted in damage in northern and eastern suburbs, and intensities up to 8 have been suggested for parts of the city (Cowan *et al.*, 1994). Severe shaking also occurred in 1901 and 1922 (Brown & Weeber, 1992). In 1922, the severity of damage in Christchurch was second only to that of the 1869 earthquake (Dibble *et al.*, 1980). In 1946, a magnitude 5.4 earthquake centered in Pegasus Bay resulted in severe ground shaking (MM7) at Christchurch. Forty-one years later a magnitude 5.4 earthquake once again centered in Pegasus Bay produced intensities of MM7 in Christchurch (Brown & Weeber, 1992). The ten largest Canterbury earthquakes in order of descending magnitude are listed in Table 3.1.

Table 3.1 Ten largest Canterbury earthquakes (Brabhaharan *et al.*, 2005) .

Date	Magnitude	Location of epicentre
June 16th, 1929	8 (second largest in NZ)	Buller
August 31st, 1888	7.0 -7.3	North Canterbury
March 9th, 1929	7.0	Arthur's Pass
November 15th, 1901	6.9	Cheviot
June 18th, 1994	6.7	Arthur's Pass
December 25th, 1922	6.4	Motunau
November 24th, 1995	6.3	Cass
December 5th, 1881	6.0	Castle Hill
August 31st, 1870	5.5	Christchurch/Banks Peninsula
June 4th, 1869	5.75	Christchurch

3.5 CHRISTCHURCH SEISMIC HAZARD ASSESSMENT

Several seismic hazard assessment studies for Christchurch and the Canterbury region (Elder *et al.*, 1991a & b; Berrill *et al.*, 1993; Dowrick *et al.*, 1998; Yetton *et al.*, 1998; Stirling *et al.*, 2001) indicate that potential exists for relatively rare but very large earthquakes (approximately magnitude 8.0) along the Alpine fault. More frequent moderate to large earthquakes (around magnitude 6.0-7.5) can be expected in the Canterbury Plains foothills and North Canterbury area, and less frequent moderate earthquakes under the Canterbury Plains and Christchurch itself.

The Alpine fault has not produced any great to large earthquakes (magnitude > 6.5) in historic time but paleoseismic studies by Bull (1996), Yetton *et al.* (1998) and Berryman *et al.* (1992) along the fault provide evidence for great earthquakes with recurrence intervals of a few hundred years. The most recent event appears to have taken place in 1717 AD when the surface fault rupture was at least 375 km. Around 1620 AD, another earthquake occurred in the north section of the fault. Based on the earthquake recurrence pattern and rupture lengths it is thought that the Alpine fault is capable of producing a large event (approximately magnitude 8.0) in the next 50-100 years (Yetton *et al.*, 1998). Prior to Yetton *et al.* (1998), Adams (1980) had presented geomorphological evidence for large earthquakes (approximately magnitude 8.0) on the Alpine fault, with recurrence intervals of 500 years. Hull and Berryman (1986) determined an average recurrence interval of between 350 and 500 years for earthquakes of magnitude 7.4-8.0 on the southern section of the Alpine Fault. Furthermore, Eberhart-Phillips (1995) argues that the levels of seismicity on the Alpine fault are comparable to the Mojave section of the San Andreas fault, which is known historically to have generated large damaging earthquakes. Historical and instrumental seismicity records indicate that Christchurch has been, and will likely continue to be, subjected to earthquakes. Elder *et al*. (1991b) state that, in considering the seismic hazards in Christchurch it is useful to apply the law of precedence: the past is the best indicator of the future. If the Alpine fault behaves as it has in the past and the assumptions of scientists are valid, a major earthquake, possibly magnitude 8.0, is well overdue. Studies estimate there is a 46 percent likelihood of a magnitude 8.0 earthquake on the central section of the Alpine fault within the next 40 years, and a 99 percent chance of a magnitude 6.0 earthquake anywhere in Canterbury in that time frame (http://www.rsnz.org) . Furthermore, Reyners (1998) reports that the Alpine fault below ground level is moving at about 3 cm each year, but the surface fault is locked. Eventually, the tension between the two will snap like a rubber band and the surface fault will rupture, generating probably the biggest earthquake since the European settlement of New Zealand. Any earthquake of more than magnitude 7.5 would cause severe ground shaking and building damage on the West Coast, in Christchurch, Nelson and Dunedin. Road, rail, communication and electricity links across the South Island could be cut and huge landslides could dam rivers, cause flooding downstream and throw river control and hydro-electricity generation into chaos. Centres largely built on soft sediments, like Christchurch, could experience soil liquefaction from the shaking, with buildings and other structures collapsing.

Other major sources of seismic threat to Christchurch include the Ashley, Springbank, and the Pegasus Bay faults, all of which are thought capable of generating earthquakes of about magnitude 7.0, rupturing on average every 2000-10,000 years, and jointly contributing to most of the seismic hazard in Christchurch (Cousins, 2005a).

The main seismic hazards in Christchurch likely to be generated by a major earthquake on the Alpine or the Ashley faults are discussed next.

3.5.1 GROUND SHAKING

Ground shaking is widely considered to be the primary cause of damage to structures, loss of life and injuries due to earthquakes (Bird & Bommer, 2004). The expected ground shaking in Christchurch from a local earthquake, a foothills earthquake and an Alpine fault earthquake are summarised in Table 3.2 below. These three scenarios are thought capable of causing MM7 to 8 shaking intensities in Christchurch (Brabhaharan *et al.*, 2005).

Table 3.2 Expected ground shaking in Christchurch from earthquake scenarios (from Brabhaharan *et al.,* 2005).

Event	Magnitude/distance	MM Intensity	Duration
Local earthquake	M 5-5.5, closer than 20km	7.0 possibly 8.0	5s to 10s
Foothills earthquake on the Ashley, Springbank, Porters Pass-Amberley faults	M 7 -7.2, closer than 50km	8.0	30s
Alpine fault	M8, at 75-150km	7.0 – 8.0	60s or more

In general, for a given site and distance from the earthquake source, ground shaking severity is directly related to the magnitude of the earthquake. In other words, the larger the earthquake, the more severe the ground shaking. However, the surface geology at a site can have a significant effect on the level of shaking during an earthquake. Earth materials, for example, bedrock, sand, gravel, silts and muds, all respond in different ways to shaking. Thick dry sediments can amplify the shaking. Shaking can also be amplified in higher parts of steep hilly areas because the waves are focussed by the shape of the land surface. The intensity of the shaking of unconsolidated sediments may be more severe than the intensity of shaking on bedrock (Rojahn, 1994). Damage to structures from shaking depends on the type of construction. Concrete and masonry structures are brittle and thus more susceptible to damage. Wood and steel structures are more flexible and thus less susceptible to damage (Dowrick, 2003).

Studies by Dowrick *et al.* (1988), Elder *et al. (*1991b) and Christchurch Engineering Lifelines Group (1997) indicate that the ground shaking in Christchurch during an earthquake will be considerably affected by the relatively soft sediment and thick sequence of gravels, sands, and silts underlying the city. This will result in major changes in the nature of the earthquake shaking by modifying the ground acceleration, velocity, and displacement at any frequency. In many areas of the city, the earthquake vibrations will be amplified. As a result, the overall average hazard for the city increases when compared to areas on bedrock (for example, most of Banks Peninsula), by approximately 0 to 2 MM intensity units or by 0 to 1 MM intensity units when compared to areas on 'average ground' comprising shallow sediments.

3.5.2 LIQUEFACTION

Liquefaction is the temporary conversion of unconsolidated soils into a medium that behaves like a fluid. It occurs when earthquake ground motion is of such high acceleration and long duration that an increase in the pore water pressure in saturated soils (usually sand and silt) results in a quicksand-like condition (Reiter, 1990). The soil response depends on the mechanical characteristics of the soil layers, the depth of the water table and the intensities and duration of the ground shaking. If sandy or silty soil is loosely packed and saturated with water, it can behave like a liquid when it is shaken strongly during an earthquake. It loses its strength, so that cars and even buildings can sink into the ground. The soil changes from solid to liquid abruptly. Liquefaction can occur several times at the same site. Soils that have liquefied in the past can liquefy again in future earthquakes. The Christchurch Engineering and Lifelines Group (1997) report that if liquefaction occurs in the city, the resulting damage can be phenomenal. Liquefaction-induced soil deformation can occur as:

1) Flow failure, where ground on even very gentle slopes moves laterally. In Christchurch, this may occur wherever lateral support to the soil is low, such as along riverbanks or the edges of the estuary;

2) Ejection of sand onto the ground surface;

3) Post liquefaction consolidation, with consequent ground settlement;

4) Large ground oscillations.

Damage from liquefaction can result in:

1) Flotation of buried structures (e.g manholes and large pipelines);

2) Lateral spreading of ground on gentle slopes;

3) Settlement of large areas due to consolidation and liquefied soil being ejected through surface cracks; and

4) Foundation failures as the liquefied soil lose its shear strength and its ability to support foundation loads.

Elder *et al.* (1991) note that the potential for liquefaction at Christchurch is of great concern because it is located near a saturated, sand- and silt-rich prograding coastline. Large areas of the city are underlain by sands and silts which, if sufficiently loose, would be highly susceptible to liquefaction. Damage from liquefaction-induced lateral movement is usually much more extensive and serious than from any settlement and the magnitude of the movement is much greater. Hence, areas along riverbanks are particularly susceptible. In Christchurch, this includes most of the lower Avon and Heathcote Rivers. The Waimakariri upstream of the bridges on State Highway 1 has gravel banks and liquefaction is not expected to occur (Christchurch Engineering Lifelines Group,1997). However, interpretations of the liquefaction hazard in Christchurch vary greatly (Brown & Weeber, 1992; Christchurch Engineering Lifelines Group,1997; McManus & Berrill, 2001; Beca Carter Hollings & Ferner, 2004).

3.5.3 LANDSLIDES

Landslides are often triggered by earthquakes. These can be very destructive and cause property damage and loss of life. For Christchurch, the risk of damage by landslide on a significant level is increased if the earthquake occurs in the two to four month period of mid-winter to early spring when soil moisture levels are high enough to reduce the apparent cohesion of the loessial soils on Port Hills. Local sites may retain high moisture contents over much of the year, and therefore be prone to landsliding over longer periods. During drier conditions, damage is likely to be confined to shallow soil falls from steep batters, rockfall from bluffs and cliffs and rockfall from higher up the hillsides. The areas most at risk are generally at the foot of the steep slopes adjoining the valleys and flood plain (Christchurch Engineering Lifelines Group,1997). However, liquefaction-induced landsliding in alluvial materials along the lower reaches of the Avon and Heathcote rivers, and around the margins of the estuary, may be a more significant hazard (Elder, *et al.*, 1991). In addition, landslides can have a great long-term impact because their huge sediment loads could choke drainage systems causing floods. This has implications for river control, bridges and services may not be fully restored for months or even years (http://www.rsnz.org).

3.5.4 TSUNAMI

Tsunami is a Japanese word for "harbour wave" and is often referred to as seismic sea waves. They represent the most serious of all natural phenomena to affect coastal areas. The most common causes of tsunami are earthquakes, coastal or submarine landslides, or volcanic phenomena. Tsunami can be considered as either near-field or far-field, and this is critical with respect to available warning time and hazard mitigation.

New Zealand lies in an active seismic area on the edge of the Pacific Ocean and is therefore prone to tsunami of local, regional and distant origin (Civil Defence and Emergency Management (CDEM), 2005). Local tsunami could be generated by ruptures on the north Canterbury faults that extend offshore. The steep sea floor near the Kaikoura Canyon, north of Christchurch may be conducive to both seismogenic and aseismic landslides, which could potentially generate tsunami (Campbell, J.pers.comm.2005). Furthermore, the Pegasus Bay fault zone also poses a severe potential tsunami hazard (Davies, T. pers comm. 2006).

Ridgeway (1984) reports that hazard from tsunami of distant origin comes mainly from the South American coast. Earthquakes from any region on the rim of the Pacific extending from the Southern Chilean coast to the Aleutian Islands are capable of causing tsunami, which could cause damage in New Zealand. The effects of tsunami from this source are much more noticeable on the east coast than the west coast of the South Island, particularly in the harbours of Banks Peninsula. Between 1848 and 1977, fifteen tsunami with South American sources are reported to have reached New Zealand, with twelve of these on the east coast (Ridgeway, 1984). Travel times vary up to 12 hours for a tsunami to arrive in New Zealand from South or North America. The Pacific Tsunami Warning Centre in Hawaii usually has sufficient time to determine the epicentre of a large earthquake, to find out whether a tsunami has been generated and to inform countries throughout the Pacific. However, the Pacific Tsunami Warning Center does not provide warning of tsunami from the South West Pacific, the Southern Ocean or close to New Zealand waters. Tide gauges on Raoul Island and the Chatham Islands give about one hour of warning for New Zealand far-field events (Downes & Stirling, 2001). Furthermore, New Zealand has not yet developed the capability to monitor for regional or local source tsunami. Capacity to receive alerts and communicate a warning for regional source tsunami is undeveloped and there is little practical warning possible for the arrival of a local source tsunami (CDEM, 2005). Since organized European settlement in 1840, the biggest recorded tsunami in New Zealand was caused by an earthquake centred on the west coast of South America in 1868, producing an estimated 6-metre high wave in Lyttelton Harbour at 4am on 15th August. Boats were capsized or swept from their moorings, and irregular tide and wave activity continued for several days. In 1960, the east coast of New Zealand experienced another tsunami produced by an earthquake centred in Chile. A wave with a peak to trough height of 5.5 metres arrived in Lyttelton. In the estuary of the Avon and Heathcote rivers boats were swept from their moorings, and the sea crossed the main road at Monks Bay, even though the tide was only in mid range. Erratic tides and wave action continued for three days, although not reaching the level of the first waves (Brown & Weeber, 1992).

Far-field tsunami are known to reach 30 m above sea level and up to 10 m are not uncommon. Significant vulnerability exists in several bays around Akaroa and Lyttelton Harbours, particularly on land adjacent to estuaries and creeks and/or lower than 5 m above mean sea level. In Lyttelton Harbour access to the communities of the southern shore could be cut off at Teddington. In Christchurch, some 30,000 people are at risk from tsunami in the New Brighton area, with property damage likely to be severe as they are believed to be living at elevations lower than 30 m near the coast (Kirk & Todd, 1994). Furthermore, all openings in the coastal dune systems could become conduits whereby the sea would enter the city, and there could be large scale flooding associated with extreme water level entering the Avon-Heathcote estuary putting people and properties at risk (Kirk & Todd, 1994).

In New Zealand, tsunami research is relatively young (compared to other geological hazards). In January 2005, in response to the Boxing Day tsunami in the Indian Ocean, a tsunami hazard and risk study was undertaken by a group of specialists at the Institute of Geological and Nuclear Sciences. All the likely sources of tsunami that could possibly affect the principal urban centres around the New Zealand coastline were examined. This was the first probabilistic tsunami risk study undertaken in New Zealand. Potential losses were estimated in terms of lives lost, injuries caused and the cost of building damage. The potential for loss of life was presented on the basis of there being no warning of the arrival of a tsunami. The modelled median estimate of damage to property from a tsunami was reported to be approximately twice that of an earthquake of a similar return period (Berryman, 2005).

3.5.5 FIRE

Thomas *et al.* (2005) state that for the most part, earthquakes are not accompanied by fire. Losses due to fire following earthquakes can be light (e.g. ChiChi Earthquake, Taiwan, 1999), quite often they are moderate (Northridge Earthquake, USA, 1994) and very infrequently, they are disastrous (San Francisco, USA, 1906). The loss of life and property caused by fire occurs in a different time frame than the structural and property damage caused directly by the earthquake. Whilst majority of the loss caused by shaking occurs during the time of ground movement, there is usually no fire loss during that time. Fire loss directly attributable to the earthquake begins instantly after the earthquake and can continue for days afterward. The destruction potential associated with post-earthquake fires is strongly dependent on the damages to the community lifeline systems, such as natural gas lines and power lines, and to the weather conditions, especially the wind speed. The problem is compounded if water lines are also broken during the earthquake since there will not be a supply of water to extinguish the fires once they have started (Evans *et al.*, 1997).

Although New Zealand has been shaken frequently by major earthquakes during its 160 years of European history, post-earthquake fire has only once been significant as shown in Table 3.3. That was following the 1931 Hawke's Bay earthquake where post-earthquake fire was probably the major cause of loss to commercial buildings. The evolution of New Zealand's (and in particular Wellington's) early building stock reflects an ironic inter-relationship between fires and earthquakes. The frequent loss of early timber buildings from fires led towards a trend to construct in more fire-resistant masonry. The extensive use of brick in the late 19th and early 20th century led to the significant urban earthquake risk that is still being addressed today (Evans *et al.*, 1997).

Table 3.3 New Zealand's experience of fire losses following major earthquakes (Thomas *et al.*, 2005).

Event Name	Date	Magnitude	Main Locality Affected	Fire Losses
Marlborough	16th Oct 1848	7.8	Wellington	None
Wairarapa	23rd Jan 1855	8.1	Wellington	None
Murchison	16th Jun 1929	7.7	Murchison	None
Hawke's Bay	3rd Feb 1931	7.8	Napier	Conflagration
Pahiatua	5th Feb 1934	7.4	Pahiatua	None
Wairarapa	24th Jun 1942	7.2	Masterton	Minor
Inangahua	23rd May 1968	7.2	Inangahau	None
Edgecumbe	2nd Mar 1987	6.5	Edgecumbe	None

To date, no specific study on fire following an earthquake has been carried out for Christchurch. The most significant NZ research in this field was by Cousins *et al*. (1991) in which losses due to fires triggered by major earthquakes in central New Zealand were estimated. A scenario-based approach was adopted, using expected numbers of ignitions from a relationship based on data from 20th century earthquakes in North America. Also, the Geological and Nuclear Sciences (GNS Science) developed "CityAware". As previously discussed in Chapter 2, "CityAware" is a GIS- based system for modelling losses due to a range of earthquake related phenomena including ground shaking, landslides, liquefaction and fire. As a pilot project it included a qualitative module for modelling and displaying the spread of fire. Factors taken into account by the module included building separation, ground slope, and wind. The fire module was further developed jointly by IGNS and Victoria University of Wellington and can now be used for high-level and detailed quantitative modelling of fire spread (Cousins *et al.*, 2002; Thomas *et al.*, 2002; Cousins & Smith, 2004; Thomas *et al.*, 2005). High-level modelling is intended for planners and policy makers, to provide answers to questions such as "is it worth creating parks in certain areas of the city to provide firebreaks?", or "what are the potential losses due to post-earthquake (uncontrolled) fire spread?" At a detailed level the module is intended to assist risk modellers and emergency managers visualise and respond to the spread of a major fire (Cousins *et al.*, 2002). The project represents the most significant element of research in this field current in New Zealand.

3.6 ELEMENTS AT RISK

This study considers two major elements at risk from earthquakes in Christchurch City:

buildings and population.

3.6.1 POPULATION

Christchurch has the second largest population of all New Zealand territorial authorities after Auckland and is the largest urban centre in the South Island. It has a population (usually resident) of 316,227 (http://www.stats.govt.nz). Between 1996 and 2001, the City's population increased by 2.3 per cent (a rate of 0.5 per cent per annum) (Table 3.4). During this time the population density for Christchurch's urban area increased from 20.3 to 20.9 people per hectare. Although the City's population is growing, the rate of growth has slowed. According to Statistics New Zealand's medium population projection, Christchurch City's resident population is expected to increase to 379,000 by the year 2026. Furthermore, the median age of Christchurch's population has increased substantially over recent decades from just less than 28 years in 1976 to 35.5 years in 2001. By 2021 the median age is expected to reach 41.6 years. This is an indication that the population is ageing. By 2021, the population aged over 65 years will increase and will make up 19 per cent of the City's total population, compared to 14 per cent in 2001. In contrast, the proportion of the population aged between 0 and 14 years will decrease to 15 per cent by 2021, down from 19 per cent in 2001 (http://www.ccc.govt.nz). These two age groups include those most likely to require assistance following an earthquake. Furthermore, commuting is the norm in the city and an estimated 168,000 people are employed in the city (http:www.stats.govt.nz). Assuming that nearly everyone works in, or close proximity to buildings, many more people are exposed to the earthquake hazard during the day. The daily cycle of movement within, into, and out of the city maintains a major difference between the night and daytime distribution of people within the study area (Aggett, 1994).

Table 3.4 Change in Christchurch's population between 1986 and 2001 (http://www.ccc.govt.nz).

Year	1986	1991	1996	2001
Total population	282,216	289,074	309,030	316,227
Numeric change (over 5 yrs)		6,858	19,956	7,197
Percentage change (over 5 yrs)		2.4	6.9	2.3

3.6.2 BUILDINGS

The buildings in Christchurch city comprise a range of types reflecting steady development over more than 100 years and range from wood, unreinforced masonry and brick buildings to modern multi-storey steel and reinforced concrete buildings. Refurbishment and redevelopment for new uses has meant some of the unreinforced masonry and brick buildings have undergone some levels of strengthening (http://www.ccc.govt.nz). The first New Zealand code requiring design for earthquake loads was adopted in 1935, following the Napier earthquake. The code was subsequently revised in 1965, 1976, 1984 and 1992. A further updated code, NZ1170.5, has been published but has not yet been adopted as a compliance document by the Department of Building and Housing. The code amendments of 1935, 1965 and 1976 all introduced significant changes in the design loads. All buildings designed prior to 1976 could therefore be regarded as "at risk from earthquake" in comparison with the current code. In addition it is now realised that the presence of "critical structural weaknesses" can also put buildings at risk regardless of their age. Such weaknesses include structural discontinuities, plan irregularity, and insufficient gap between buildings.

The Building Act 1991 defines "earthquake prone buildings" as buildings constructed principally of reinforced concrete or masonry which are likely to suffer collapse when subject to earthquake shaking equivalent to 50 per cent that specified in the 1965 code. This is equivalent to about 10 per cent of the current code. These buildings are principally pre-1935 brick buildings. Christchurch City Council has a list of "potentially earthquake prone buildings." These are generally pre-1935 buildings that have had no significant structural upgrading recorded. However, many of these have not had calculations to confirm their status. The list is therefore not accurate, and has not been updated recently due to forthcoming changes in the legislation (as noted below).

The Buildings Act 2004, most sections of which came into effect either on 30th November 2004 or 30th March 2005, redefines "earthquake prone buildings" as any building likely to suffer collapse when subject to an earthquake equivalent to 33 per cent of current code. This change will significantly increase the number of "potentially earthquake prone buildings" on Council lists (Taylor, J. pers comm. 2005). Furthermore, to make buildings safer for use in the future, the Building Act 2004 introduced provisions to improve the likelihood of existing buildings withstanding earthquakes. This is a long-term strategy that focuses on the buildings most vulnerable in an earthquake. It does not include small residential buildings (http://www.building.govt.nz). As part of the requirements of this Act, the Christchurch

City Council developed a policy on potentially earthquake prone buildings in their area of jurisdiction. The policy, which is currently being reviewed after receiving public comment, considers how the buildings will be prioritised for improvement, and the design loads for the upgraded structures (Taylor, J. pers comm. 2005). An attempt to obtain some indication of the number of buildings that may be affected by the new requirements was made by the Council by examining a summary of the number of buildings in the city built since pre-1930. It was estimated that about 16,406 Christchurch buildings are potentially affected by the changes under the Act (this excludes residential buildings of one storey and those that are two or more storeys with fewer than three household units). It was assumed that buildings built after 1979 comply with the "new building" standard. In addition, of the 550 buildings that are listed on the City Plan heritage list, 350 are affected by the seismic upgrading requirements of the Act. It is important to note, however, that this information is tentative and property files still need closer examination to isolate the premises that may need further consideration (http://www.ccc.govt.nz).

The New Zealand Society for Earthquake Engineering is also promoting a Grading Scheme for earthquake risk buildings to increase public awareness and encourage building owners to carry out improvements to their building to achieve a more desirable grade. Although the Grading Scheme is still only in draft form, it marks a new milestone in the understanding and practical assessment of older buildings and their likely behaviour when subject to earthquake. The grading is from A (100 per cent current code) to E (less than 20 per cent of current code). It is hoped that Councils will adopt the grading scheme as part of their policy. However, proper implementation is obviously some years away (Taylor, J. pers comm. 2006).

3.6.3 EARTHQUAKE INSURANCE

The Earthquake Commission (EQC) is New Zealand's primary provider of natural disaster insurance to residential property owners. EQC pays out on claims from residential property owners for damage caused by earthquake, natural landslip, volcanic eruption, hydrothermal activity, tsunami, in the case of residential land, a storm or flood, or fire caused by any of these. Dwellings are insured up to a maximum of $100,000 plus Goods and Services Tax (GST) and personal effects are insured up to a maximum value of $20,000 plus GST. Dwellings are covered on a replacement value basis. Personal property is insured on the same basis as the household insurance policy covering the same property (http://www.eqc.govt.nz).

3.7 SUMMARY

Christchurch is known to have suffered large earthquakes in the past, and scientific evidence suggests that this trend will continue. One of the major threats to the city is from a magnitude 8.0 earthquake generated on the Alpine fault. Other major sources of seismic threat include the Ashley, Springbank and the Pegasus Bay faults, which are all thought capable of generating earthquakes of about magnitude 7.0. Either of these events would expose the city to seismic hazards such as ground shaking, liquefaction, landslides and possibly fires. Such hazards would have disastrous consequences for the people, buildings, lifelines and the socio-economic structure of the city.

CHAPTER 4

CHRISTCHURCH SEISMIC RISK ASSESSMENT –

SEISMIC HAZARD MODEL

4.1 INTRODUCTION

Several component models are used in the present seismic risk assessment study as follows: (1) seismic hazard including attenuation of earthquake shaking and microzonation; (2) building inventory; (3) population distribution; (4) building damage; (5) building collapse; (6) economic loss and (7) casualty rates. This chapter gives a description of the seismic hazard model, the main components of which are highlighted in Figure 4.1.

4.2 SEISMIC HAZARD MODEL

There are two fundamental types of seismic hazard assessment: (1) deterministic and (2) probabilistic. A deterministic seismic hazard assessment (DSHA) uses discrete, single-valued events or models to arrive at scenario-like descriptions of earthquake hazard (Reiter, 1990). The most common form of this method is use of the largest earthquake known to have occurred in a region. This approach is based on a premise that is geologically sound (FEMA, 1989). A probabilistic seismic hazard assessment (PSHA) on the other hand, identifies all possible earthquakes that could affect a site; including all possible combinations of magnitude and distance, and the characterisation of the frequency of occurrence of different earthquake sizes. In this study a deterministic

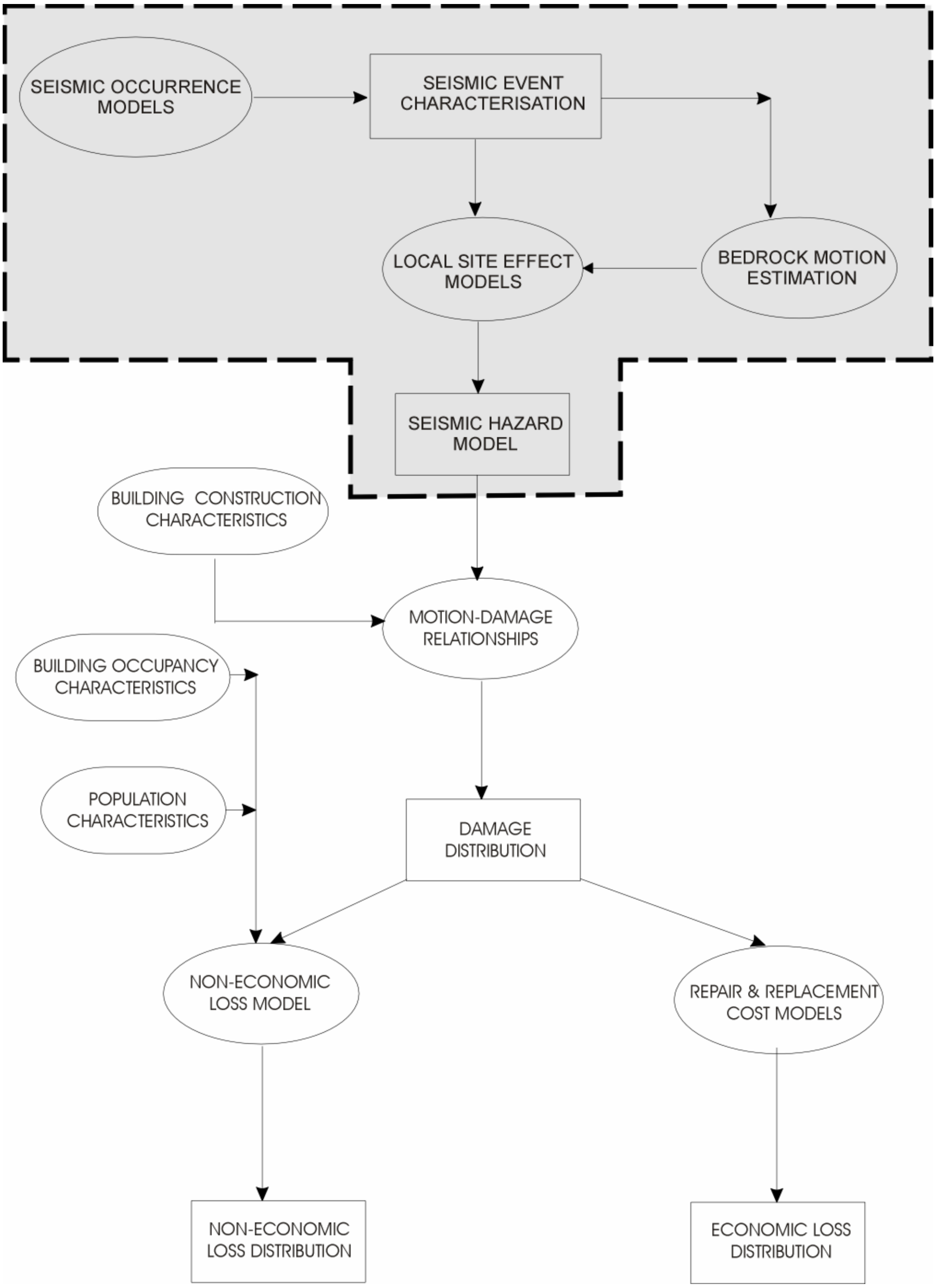

Figure 4.1 Components of a seismic risk assessment methodology. Components which are discussed in this chapter are highlighted (modified after King & Kiremidjian, 1994).

seismic hazard model is used. A typical DSHA can be described as a four step process (Kramer, 1996) consisting of:

1) Identification and characterisation of all earthquake sources capable of producing significant ground motion at the site. Source characterisation includes definition of each source’s geometry (the source zone) and earthquake potential;

2) Selection of a source-to-site distance parameter for each source zone. In most DSHAs, the shortest distance between the source zone and site of interest is selected. The distance may be expressed as an epicentral distance or hypocentral distance, depending on the measure of distance of the predictive relationship (s) used in the following step;

3) Selection of the controlling earthquake, that is, the earthquake that is expected to produce the strongest level of shaking; generally expressed in terms of some ground motion parameter, at the site. The selection is made by comparing the levels of shaking produced by earthquakes (identified in step 1) assumed to occur at the distances identified in step 2. The controlling earthquake is described in terms of its size (usually expressed as magnitude) and distance from the site;

4) The hazard at the site is formally defined, usually in terms of ground motions produced at the site by the controlling earthquake. To obtain a complete predictive model for the ground motion at a given site, it is

necessary to (a) describe fully the ground motion at the source, and (b) describe the changes to the ground motion as it propagates from source to site, i.e. the attenuation (Dowrick, 2003). A description of the attenuation model, which has been largely derived from Cousins (2005a), is given in section 4.2.1 of this chapter.

In this study the principal hazard considered is earthquake ground shaking due to two earthquake scenarios: (1) a magnitude 8.0 earthquake on the Alpine fault, at a distance of 130km from Christchurch, which produces MM7 shaking intensity in the city and (2) a magnitude 7.0 earthquake on the Ashley fault, at a distance of 25 km from Christchurch that produces MM8 shaking intensity in the city.

It is important to note that a DSHA does not provide information on the probability of occurrence of the controlling earthquake, the likelihood of it occurring where it is assumed to occur, the level of shaking that may be expected during a finite period of time, or the effects of uncertainties in the various steps required to compute the resulting ground motion characteristics (Kramer, 1996).

4.2.1 ATTENUATION MODEL

In this study, the Dowrick and Rhoades (1999) attenuation model was used (Figures 4.2 and 4.3). This model is the most recent MMI model for New Zealand and it takes into account the magnitude and location of the earthquake as well as its focal depth, mechanism and orientation of the fault source. For each scenario earthquake, the likely ground motion at locations of interest can be estimated. Smith (2003) reported that Dowrick and Rhoades (1999) used the MM intensity, rather than peak ground

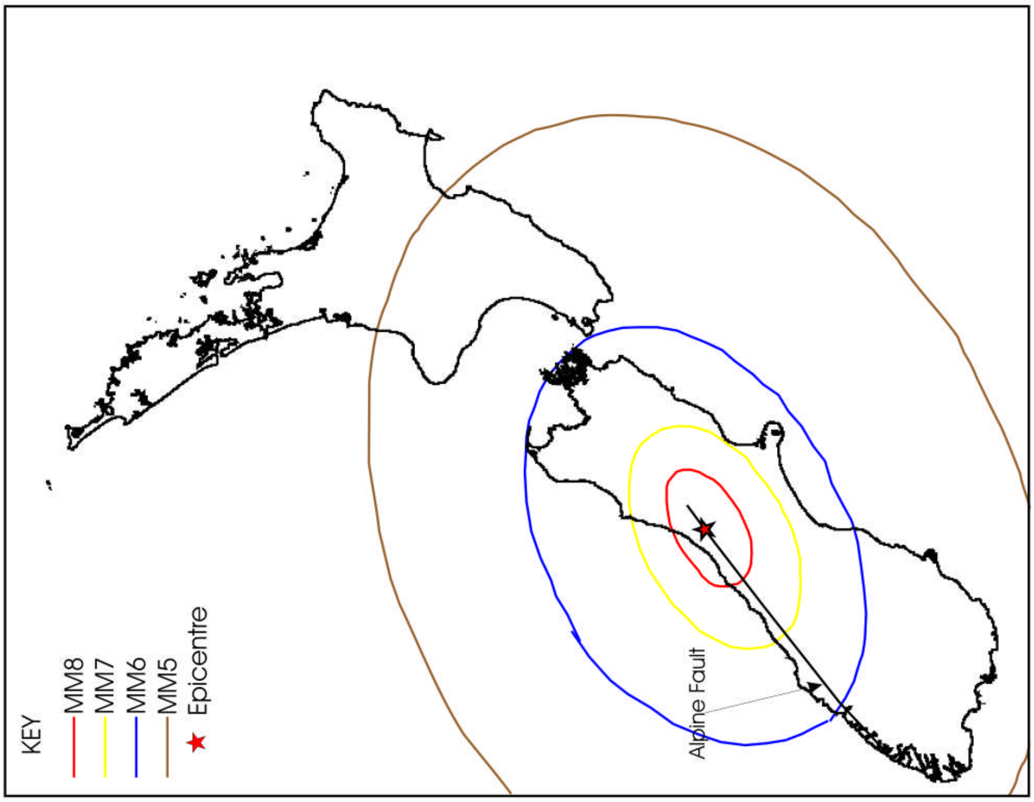

Figure 4.2 Assumed intensity distribution for a magnitude 8.0 earthquake on the Alpine fault (source: Cousins, J. pers. comm.2005).

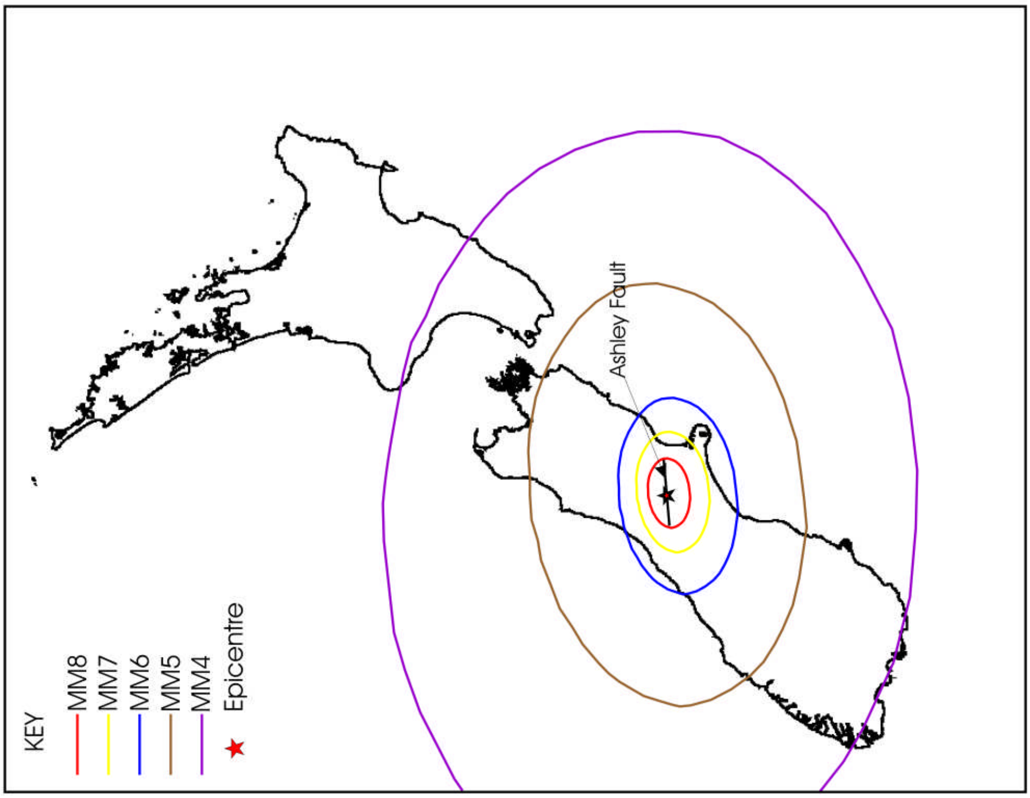

Figure 4.3 Assumed intensity distribution for a magnitude 7.0 earthquake on the Ashley fault (source: Cousins, J. pers.comm. 2005).

acceleration (PGA) or spectral acceleration, because damage ratio data are collected and analysed for intensity zones (i.e. MM7, 8, etc) so they can be applied only in terms of MM intensity. Furthermore, Smith (2003) argues that the common practice of first calculating PGA, then converting it to MMI, is fraught with difficulty because of the high frequency content of PGA from small earthquakes at short distances. At high frequencies the PGA may be high but the effect on buildings is small. Dowrick and Rhoades (1999) have provided a function which estimates MM intensity directly, and is reported by Smith (2003) to be the best tool for the purpose of using the damage ratio information.

A more recent study by Smith (2002) has added a slight modification to the Dowrick and Rhoades (1999) formula for intensity. Smith (2002) noted that the database of large earthquakes that was available to Dowrick and Rhoades (1999) included very few earthquakes that had long surface fault ruptures, for which intensities would be expected to be quite high along the full length of the rupture.

The modification proposed by Smith (2002) takes account of the known length of a fault and extends the Dowrick and Rhoades (1999) formula, where necessary, to include the full length of the fault in the high intensity zone. Finally, an important point about the Dowrick and Rhoades model is that it predicts shaking intensities for average ground. Actual intensities on non-average ground differ from the average, i.e. shaking on soft soil is often stronger and shaking on rock is often weaker. This is a result of microzonation phenomena (Cousins, 2005a).

4.2.2 SITE RESPONSE MODEL

Soil types and thicknesses, and to a lesser extent rock, vary widely from site to site (Dowrick, 2003). Microzonation is the term used to describe how local ground effects modify the seismic shaking that is experienced at a specific site (Cousins, 2005a). Reiter (1990) reports that the effects of local ground conditions are so great that the propensity for earthquake damage at some locations may be much more dependent upon these conditions than on the proximity of nearby earthquake sources.

Several phenomena can be involved. Of most importance to seismic risk studies are amplification of shaking by soft soils, liquefaction, land sliding, and topographic enhancement of shaking (Cousins, 2005a). This study only considers the effects of amplification of shaking and liquefaction.

1. AMPLIFICATION

The amplification hazard is derived from geology on the basis of an assumed soil strength based on lithological description and local knowledge (Heron, D. pers. comm. 2005). In order to identify localised changes in earthquake hazard due to variations in ground conditions, the study area was divided into a series of site classes (Figure 4.4). These classes represent regions that are considered to have similar response to earthquake ground shaking.

Cousins (2005a) reports that amplification is most obvious when the input rock motions are relatively weak and caused by large, distant earthquakes. An unequivocal example occurred in Mexico City in September 1985 which caused

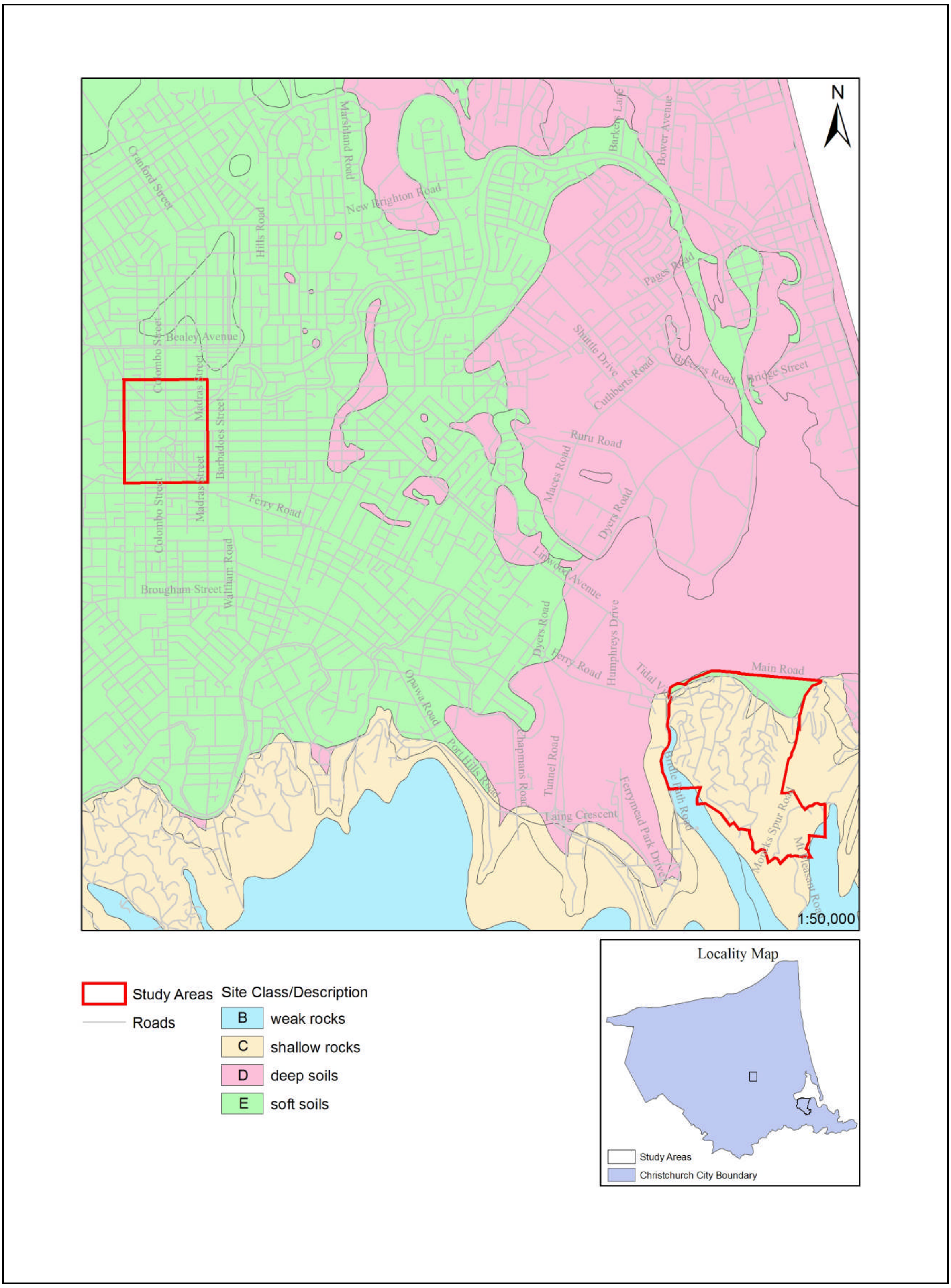

Figure 4.4 Site class map of the study areas (source: GNS Science, Unpublished data).

extensive loss of life and property. While the epicentre of the earthquake was near the Pacific coast of Mexico, and there was some damage on the coastal region, the main impact and destructiveness of the earthquake was experienced in the lake bed zone of Mexico City, approximately 400km from the epicentre where substantial amplification of the low-frequency motions occurred. The official estimate of human toll was 8000. Approximately 300 buildings in Mexico City collapsed during the main event. However, with the number of buildings demolished because they were beyond repair, the total number of buildings lost was about 1100 (Celebi *et al.*, 1987).

Cousins (2005a) argues that one reason for this was a double resonance effect. Areas of soft soils that had resonant periods of about 2 seconds were preferentially set in motion by the incoming seismic waves, and buildings that had the same resonant frequency, typically being those 8-16 stories high, swayed particularly strongly and as a result collapsed. Neighbouring buildings of weak stone construction were undamaged because their resonant periods did not match the resonant period of the soft soils. A second example occurred in San Francisco during the 1989 Loma Prieta earthquake. About 10 people died and 566 more were injured in spite of the fact that Downtown San Francisco was nearly 100 km from the epicentre of the magnitude 7.1 earthquake. Furthermore, about 40 houses were destroyed in the Marina District. On firm soils and rocky areas of the city the prevailing intensity was MM6, increasing to MM7 on some adjacent softer soils and to MM9 in some small pockets of very soft soils. However, liquefaction effects also contributed to the damage associated with the very soft soils (Cousins, 2005a). However, in 1931 when Napier was subjected to MM10 shaking from a nearby magnitude 7.8 earthquake, shaking damage increased with the strength of the subsoil. Houses on ground classified as rock were, on average, more badly damaged by ground shaking than houses on ground classified as firm soils and gravels, which in turn were more badly damaged than most houses on ground classified as soft soil. It is important to note however, that the most badly damaged houses were those constructed on soft soils which were subject to lateral spreading. These were approximately 10 percent of all houses and are excluded from this discussion (Cousins, 2005a).

In New Zealand, amplification of weak seismic shaking by soft soils has been seen several times in records made by seismological instruments in Wellington, Lower Hutt and Porirua. On the other hand, data from around the world show that peak ground accelerations and short-period vibrations appear to be attenuated on soft soils for accelerations above about 0.4g, i.e. for intensities greater than about MM8 to MM9 (Cousins, 2005a).

In summary, the presence of soil overlying bedrock modifies the excitation in a complex manner, with conflicting effects dependent on dynamic characteristics of the soil layers and the strength of the excitation (Dowrick, 2003). Amplification of seismic shaking in soft soils is expected to occur for all periods at low levels of excitation (< MM8) and for long periods (> 0.6 seconds) only at strong levels of excitation (> MM8). Furthermore, shaking intensity on average-ground lies between that of rock and soft soil, which means that relative to the average-ground shaking, as predicted by the Dowrick and Rhoades (1999) attenuation model, shaking on soft soil is often stronger and shaking on rock is often weaker (Cousins, 2005a).

2. TOPOGRAPHIC ENHANCEMENT OF SHAKING

Amplification of shaking can also occur on ridges or hilltops. A particular example is when several groups of similar houses on topographically different sites showed different degrees of damage during the 1985 San Antonio, Chile earthquake. The houses on the hilltops or ridges were heavily damaged while those on nearly flat or valley sites were only slightly damaged. An additional example is given by accelerograph recordings of two earthquakes at three adjacent rock sites across a valley in New Zealand. It was found that amplitudes on the two hilltop sites on opposite sides of the valley, were much the same as each other, but they were about twice the size of those recorded for the third site, which was near the bottom of the valley (Dowrick, 2003). Topographic effects can be extremely complex and highly variable and currently cannot be routinely included in hazard analysis (Reiter, 1990; Dowrick, 2003). For Christchurch, any topographic enhancement is expected to be restricted to the crests of ridges in the Port Hills area (Cousins, 2005a).

3. LIQUEFACTION

In this study, liquefaction hazard is derived from geology on the basis of soil age, an assumed dominant grain size and depth to groundwater, supplemented with local knowledge. As a first step, a mapping of unit code to liquefaction susceptibility was created using a regional liquefaction susceptibility technique. This technique is based on a database which records historical liquefaction-induced ground damage against shaking intensity and geological conditions. Liquefaction susceptibility is assigned to geological units on the basis of the level of shaking required to cause liquefaction-induced ground damage. Figure 4.5 illustrates the liquefaction hazard

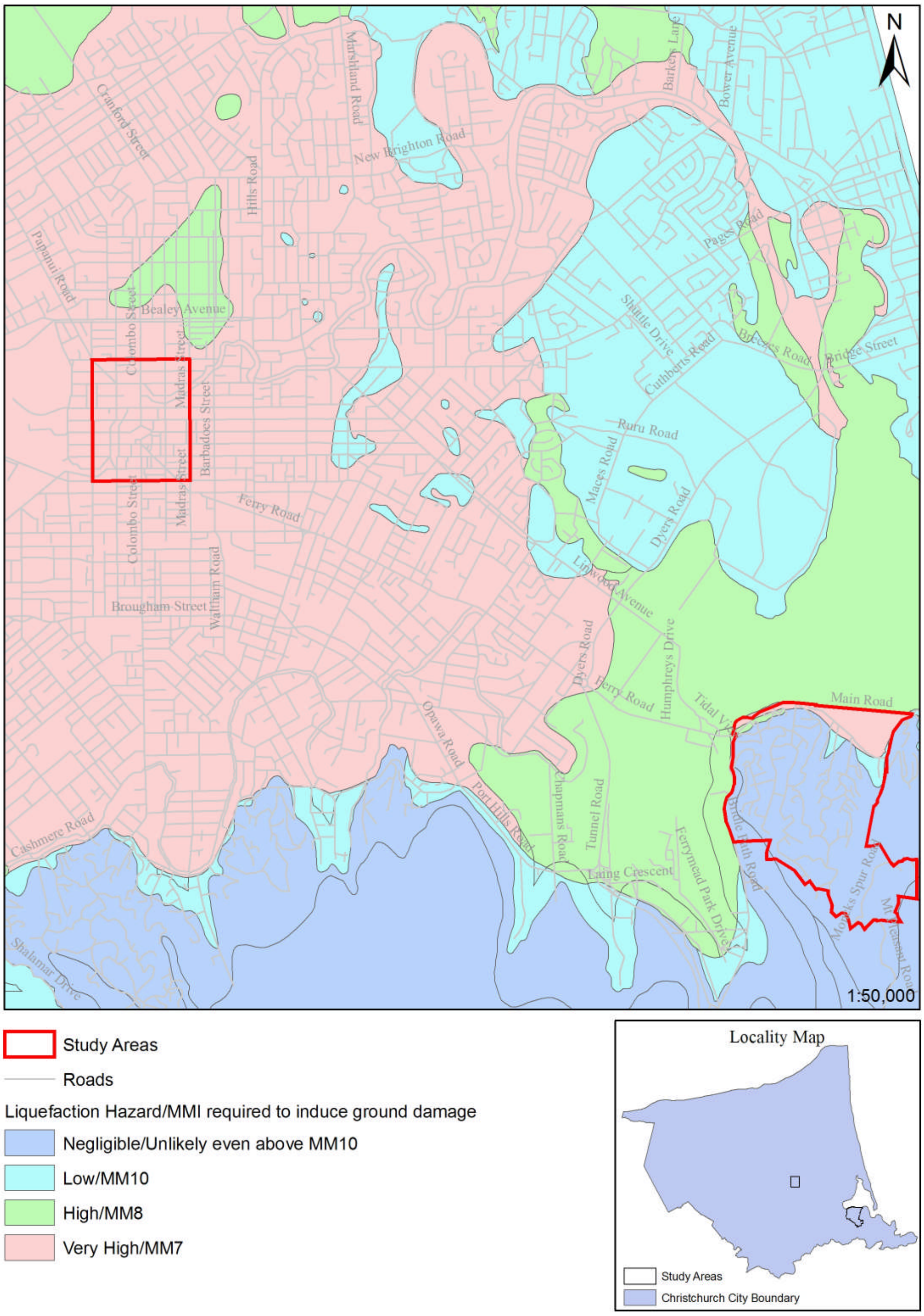

Figure 4.5 Liquefaction hazard map of the study areas (source: GNS Science, Unpublished data).

map for the study area. Compared to ground shaking, liquefaction is less likely to cause conventional collapse of buildings or fatalities. Structural damage to buildings in the conventional terms of cracking, failure of structural members and collapse or partial collapse, is rarely reported for buildings affected by liquefaction (Bird & Bommer, 2004).

In allowing for liquefaction in Christchurch, it was assumed that ninety percent of the flat land of Christchurch is "soft" and susceptible to liquefaction, but that in any particular earthquake the proportion of flat-land buildings likely to be badly affected by lateral spreading or settlement is small (5 percent) (Cousins, 2005a).

4. MICROZONATION LOSS ALLOWANCES

There are no firm data for guidance as to the increased (on soft soils) or decreased (on rock) intensities of shaking that might result from the various microzonation phenomena. As a matter of judgement the following increments relative to the average-ground intensities as predicted by the Dowrick & Rhoades (1999) model were assumed. Firstly, for soft soils, up to MM7 there is an increase in intensity of 0.5 of an MM intensity step as a result of amplification. For intensities of MM9 and above there is an increase of 0.05 as a result of lateral spread and settlement. Between MM7 and 9 there is a steady change in the increment as shown in Figure 4.6. For rock, up to MM7 there is an effective decrease in intensity of 0.5 of an MM intensity unit. From MM7 to MM9 this de-amplification becomes steadily smaller, in part due to topographic enhancement and landsliding. For MM9 and higher it is equivalent to 0.05 of an MM intensity step (Cousins, 2005a).

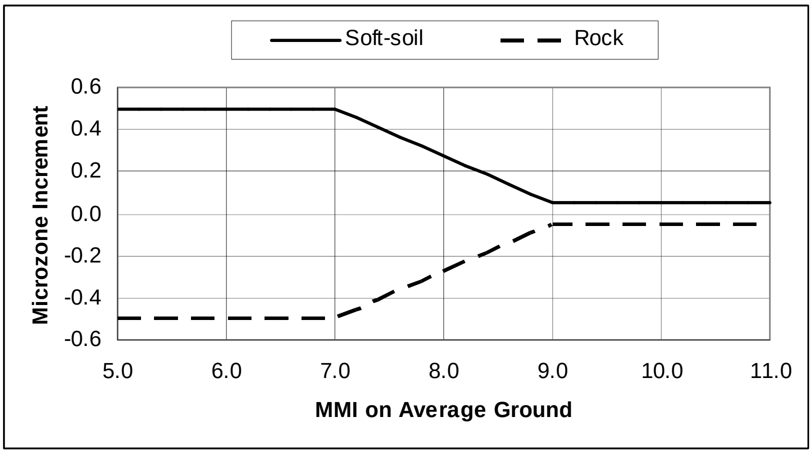

Figure 4.6 Changes in shaking intensity, relative to the "average-ground" intensity modelled by the Dowrick and Rhoades (1999) attenuation model, due to microzonation (Cousins, 2005a).

4.3 SUMMARY

A deterministic seismic hazard model was used to describe the seismic hazard in the study area due to two hypothetical earthquakes: (1) a magnitude 8.0 earthquake on the Alpine fault, and (2) a magnitude 7.0 earthquake on the Ashley fault. Ground motion is expressed as the MMI and is estimated using the attenuation model of Dowrick and Rhoades (1999). The impacts of microzonation were also incorporated into the model.

CHAPTER 5

CHRISTCHURCH SEISMIC RISK ASSESSMENT – BUILDING INVENTORY AND POPULATION DISTRIBUTION

5.1 INTRODUCTION

The next two component models of a seismic risk assessment study are as follows: (1) building inventory and (2) population distribution. This chapter gives a description of these two models and the sequence of data processing used to convert the raw data into components of the seismic risk assessment models. These components are highlighted in Figure 5.1. The platform used was the ESRI GIS software package, ArcView 9.0, which enabled the storage, manipulation and linking the many items of data needed. This chapter begins with a description of the primary sources of data used in the compilation of the building inventory. It then outlines the methodology used for calculating building replacement values and concludes with a description of the methodology used to determine the distribution of population in the study areas, in different building types, and for different times of the day.

5.2 BUILDING INVENTORY MODEL

A buildings inventory was compiled in order to better understand the physical, financial and social exposure to earthquake loss in the study area. Much of the input data for the

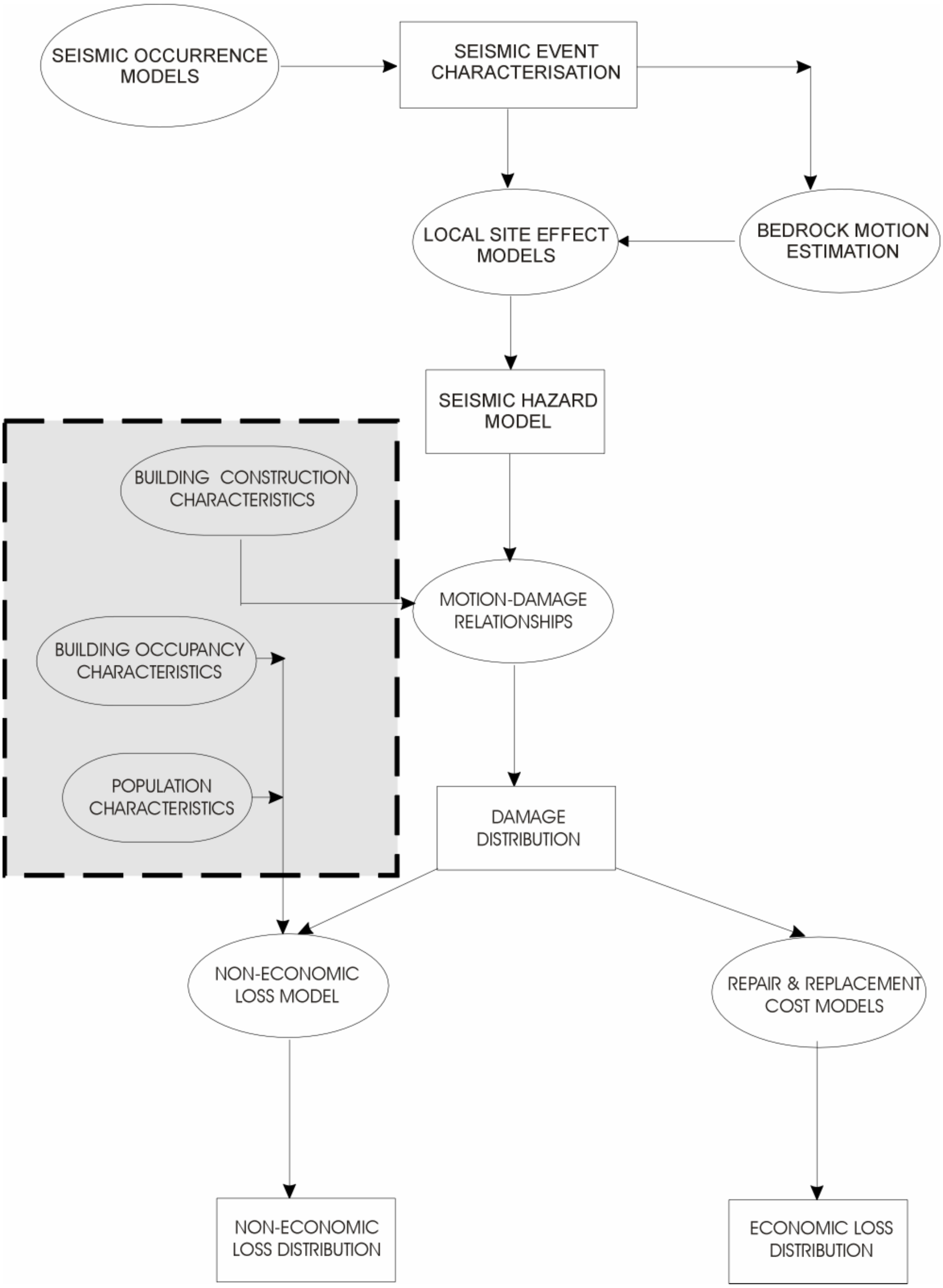

Figure 5.1 Components of a seismic risk assessment methodology. The highlighted components are those which are discussed in this chapter (modified after King & Kiremidjian, 1994).

buildings inventory was in pre-existing digital inventories of assets obtained from the Christchurch City Council. These include the property valuation and "potentially earthquake-prone buildings" databases. The property valuation data was prepared by the former Government Valuation Department for the Christchurch City Council (Sutcliffe, S. pers comm. 2005). It contains a number of attributes for each property, including valuations (capital value, land value and improvements value), address (street number and road name), areas (building footprint, total lined floor area, total floor area, main floor area and land area), the decade of construction, various use indicators (commercial, industrial, residential, etc), wall and roof construction material and legal descriptions.

The "potentially earthquake-prone buildings" data, on the other hand, is compiled and maintained by the Christchurch City Council (Bensberg, S. pers. comm. 2005) and contains the physical address of "potentially earthquake-prone" buildings and specific information on structural weaknesses such as suspended awnings, brick chimneys, parapets, etc. As described in Chapter 3, "earthquake-prone" buildings are those which are defined in the 1991 Building Act as buildings constructed principally of reinforced concrete or masonry and are highly susceptible to earthquake damage.

There is no agreed standard for creating building inventories for seismic risk assessment studies; either aggregated or highly detailed property-by-property level buildings data can be used depending on time and resources available. Most New Zealand studies to date, including one for Christchurch (Cousins, 2005a) have used aggregated buildings data to demonstrate earthquake loss modeling. An exception is a study (Cousins & Heron, 2000) for Wellington city where a detailed property-by-property level inventory was utilised. The effects of using aggregated buildings data as opposed to a highly detailed property by property level data, for earthquake damage and loss modeling has been investigated by Cousins (2004). He concludes that for a deterministic scenario, where a large earthquake affects a large urban area, the damage and loss estimates obtained from using either an aggregated or a detailed building inventory are within 4 percent of each other. When a probabilistic approach is used with many earthquakes there is a great deal of implicit averaging and the differences between building-by-building and aggregated data are usually very small (Cousins, J. pers comm. 2005).

In this study, the 2001 Census meshblock is used as the basic unit for earthquake loss estimation because it is the smallest geographic area used by Statistics New Zealand in the collection and/or processing of data (http:www.stats.govt.nz). In addition to this, building valuation data are available for each meshblock and the meshblock is also small enough to allow construction attributes of buildings and the population distribution to be described in simple proportions with sufficient accuracy for the purposes of this study. All data are hence aggregated and displayed at meshblock-scale rather than at property-by-property level. A meshblock comprises approximately sixty to ninety houses. In both study areas, there are a total of 75 data aggregates, each of which has been associated with a geographic location, which is the centroid of the meshblock. For each earthquake scenario, the MMI is estimated at each of the 75 data locations.

The different sets of data were stored in a GIS as several inter-related database tables. The use of inter-related tables helps to reduce the required data storage by eliminating repeated attributes through the use of unique identification numbers. The meshblocks were stored in a polygon theme. The non-spatial property valuation data was geocoded using address matching techniques within the GIS in order to provide spatial locations for each property in the database and then stored in a point theme. The valuation data were then aggregated at meshblock level and linked to their corresponding meshblocks by a key field, called the “meshblock_id” field.

Prior to the development of a building inventory for earthquake damage and loss modelling, two classification systems are used. These include those based on building occupancy (use) and those based on building construction type. Building occupancy (e.g., residential, commercial, industrial) information provides for the estimation of economic losses and casualties. However, information on building construction type is useful in damage estimation (Ventura *et al.*, 2005).

5.2.1 BUILDING OCCUPANCY

The buildings in the study area were classified into eight sub-groups based on the primary use of the building, including commercial, industrial, residential, utility services, transport services, community services, recreational services and multi-use at primary level. These sub-groups were then combined into two major occupancy classes, residential and non-residential. Statistical functions in the GIS were used to derive several base datasets, including total floor areas, average improvements values and replacement values for the different building occupancy classes. Replacement values, which are required for loss modeling, were estimated from the base data by using the supplied data to generate total floor areas of the building stock which were then multiplied by estimated rebuilding costs as follows:

$$\textbf{Replacement Value (\$) = Total floor area (m}^2\textbf{)} \times \textbf{Rebuilding Cost /m}^2\textbf{ (\$/m}^2\textbf{)}$$

Estimates of rebuilding costs for buildings in the two categories, residential and non-residential were obtained by dividing average property improvement value by the total square footage of properties in that particular category. Total property improvement value is the difference between the capital and land values which were derived from the property valuation data.

A summary of building replacement values and floor areas for the Christchurch CBD and Mount Pleasant are given in Tables 5.1 and 5.2 respectively. Maps of building replacement values and total floor areas by meshblock for the CBD and Mt Pleasant are given in Figures 5.2 to 5.9.

Table 5.1 Building replacement values and total floor areas for residential and non-residential buildings in the Christchurch CBD.

CBD	Residential	Non-residential
Replacement value	\$234,000,000	\$1,660,000,000
Building footprint (m^2)	82,568	467,741
Building floor area (m^2)	111,880	1,047,667

Table 5.2 Building replacement values and total floor areas for residential and non-residential buildings in Mt Pleasant.

Mount Pleasant	Residential	Non-residential
Replacement value	\$632,000,000	\$14,500,000
Building footprint (m^2)	218,108	7,516
Building floor area (m^2)	330,969	7,812

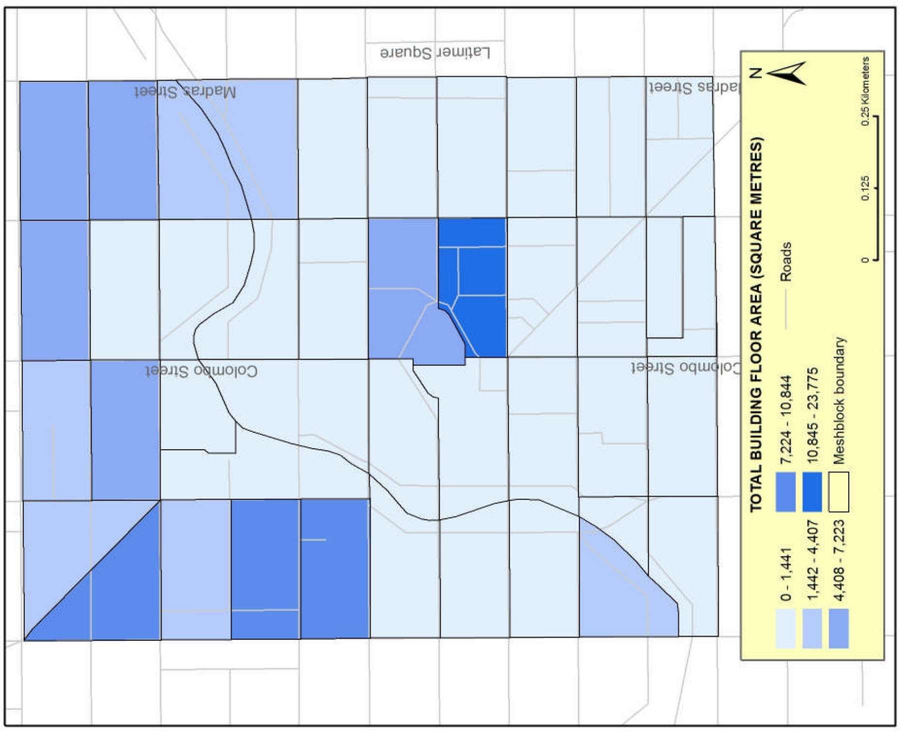

Figure 5.2 Map of total floor area by meshblock for residential buildings in the CBD.

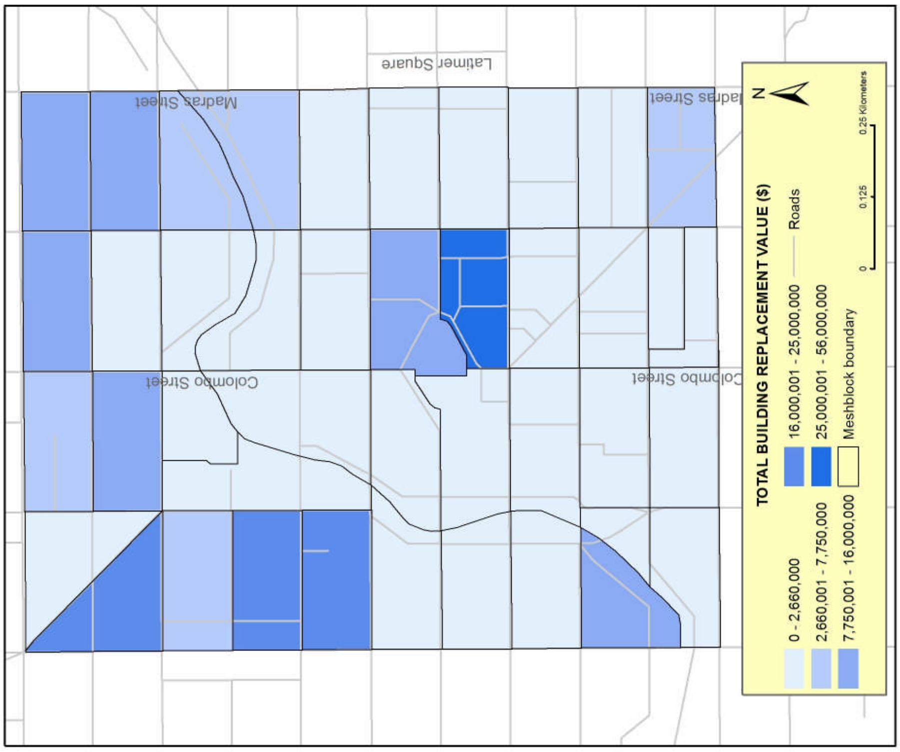

Figure 5.3 Map of building replacement values by meshblock for residential buildings in the CBD.

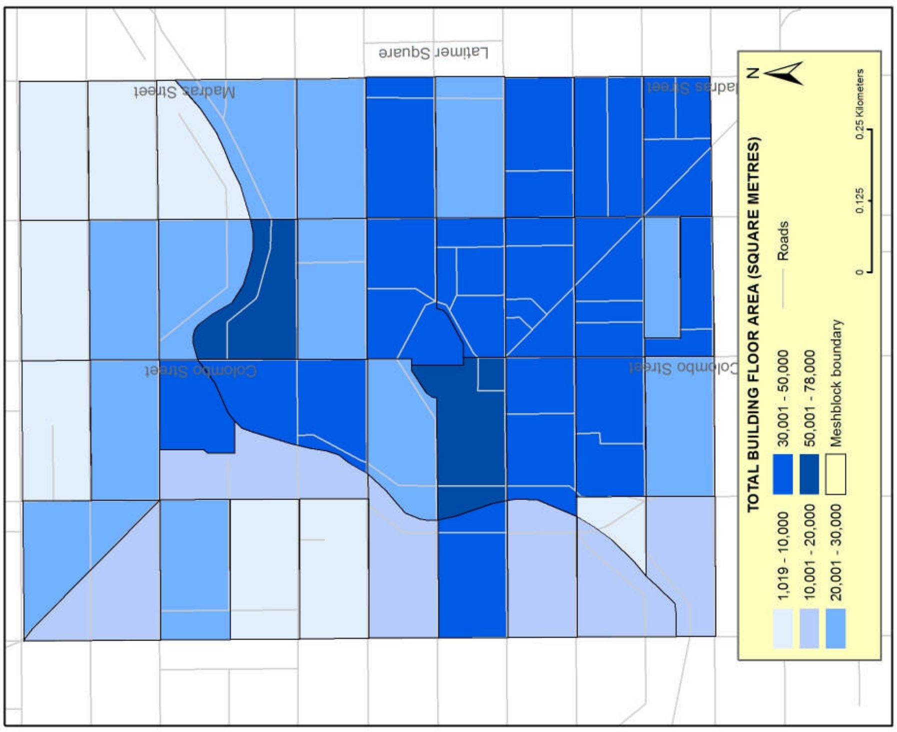

Figure 5.4 Map of total floor area by meshblock for non-residential buildings in the CBD.

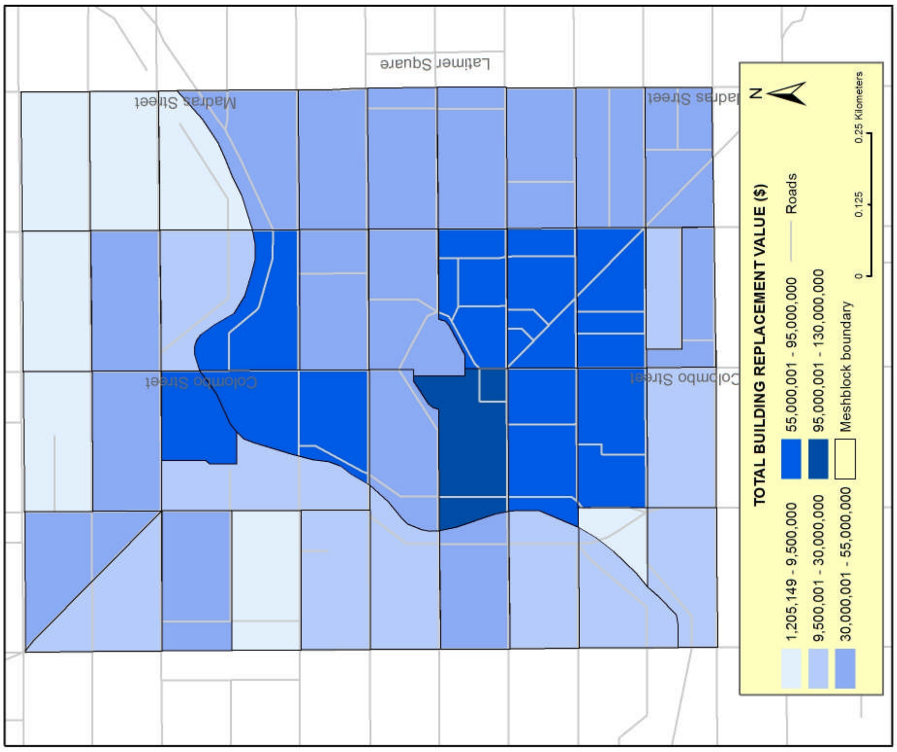

Figure 5.5 Map of building replacement values by meshblock for non-residential buildings in the CBD.

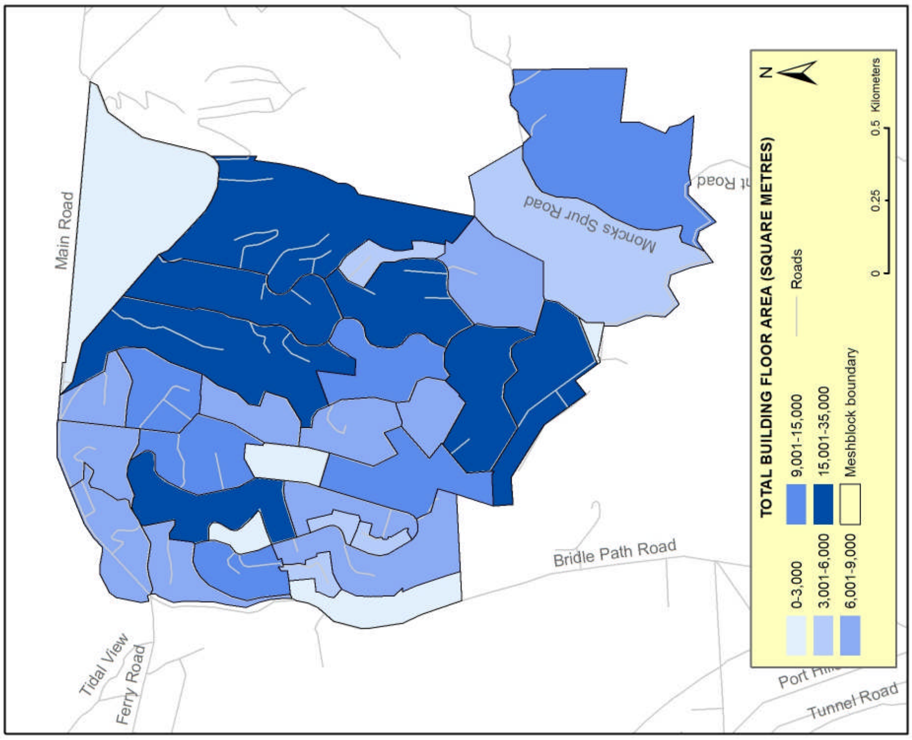

Figure 5.6 Map of total floor area by meshblock for residential buildings in Mt Pleasant.

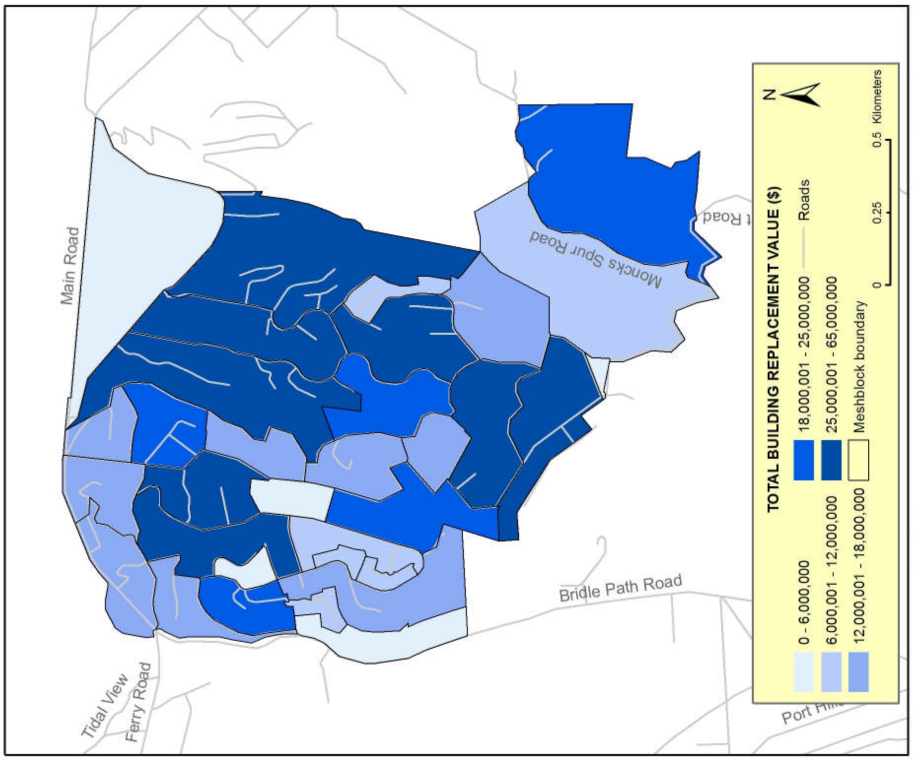

Figure 5.7 Map of building replacement values by meshblock for residential buildings in Mt Pleasant.

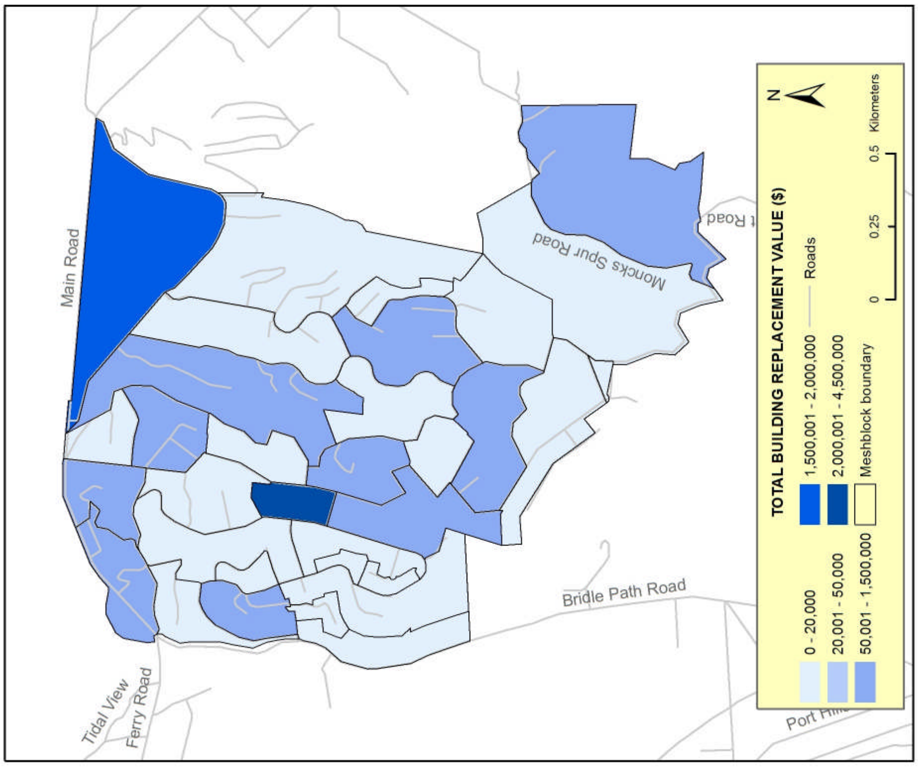

Figure 5.9 Map of building replacement values by meshblock for non-residential buildings in Mt Pleasant.

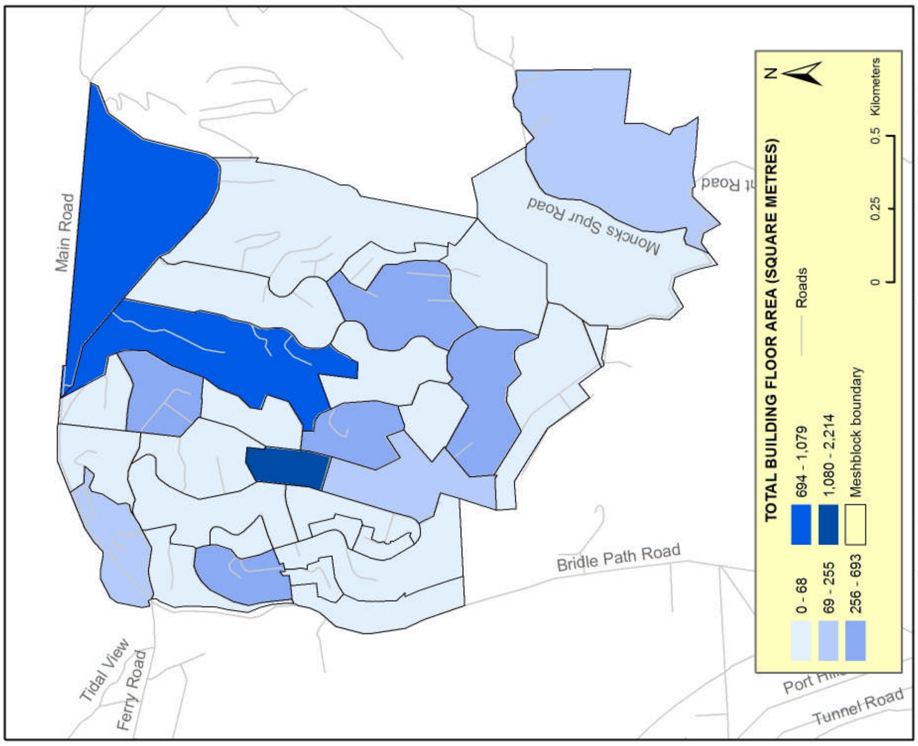

Figure 5.8 Map of total floor area by meshblock for non-residential buildings in Mt Pleasant.

5.2.2 BUILDING CONSTRUCTION

In general, the performance of a building during an earthquake depends on several factors, some of which include strength, weight, construction material, height, design and construction quality, and age. Also, the vulnerability of buildings increases when they have been subjected to earthquakes in the past (Kythreoti *et al.*, 1998). Therefore, each structure has a unique response to the ground motion generated by earthquakes based on these characteristics (Ventura *et al.*, 2005). For the purpose of a seismic risk assessment study, some or all of these characteristics can be used to group buildings into classes representing the average characteristics of buildings in that class (Ventura *et al.*, 2005).

The original property valuation data did not contain any information on load bearing elements of individual buildings. However, to assess building vulnerability to earthquakes, information is needed on the type of load-bearing structural frames and walls (e.g reinforced concrete, un-reinforced masonry or timber frame) and this information is not explicit in the property valuation data. Instead, roof and wall cladding descriptions are given. Hence, the wall cladding descriptions were used to deduce the load bearing mechanism as this is common practice in New Zealand (Cousins & Heron, 2000). Furthermore, the importance of assessing building damage using the types of load bearing elements of a building rather than simply the wall cladding, and the difference it can make to estimates of direct damage to buildings, is seen in the following example. In the 1989 Newcastle earthquake, New South Wales, Australia, cavity brick houses performed about twice as poorly as brick veneer, in terms of percentage losses of their total insured value. Houses with timber frames (brick veneer, fibro and timber cladding) all performed similarly. This example shows that there is a reasonably good agreement between the type of wall cladding and construction type (Stehle *et al.*, 2002). The composition of buildings according to external wall cladding type is given in Tables 5.3 and 5.4 below.

Table 5.3 Composition of buildings according to wall cladding type in Christchurch CBD.

MT PLEASANT WALL CLADDING DATA				
CLASS	RESIDENTIAL		COMMERCIAL	
WALL CLADDING	NUMBER	PERCENTAGE	NUMBER	PERCENTAGE
brick	486	30.9	0	0.0
concrete	403	25.7	39	60.9
fibrolite	112	7.1	0	0.0
glass	0	0.0	0	0.0
iron	0	0.0	1	1.6
malthoid	0	0.0	0	0.0
mixture	0	0.0	10	15.6
roughcast	175	11.1	0	0.0
stone	20	1.3	0	0.0
wood	279	17.8	0	0.0
data missing	96	6.1	14	21.9
TOTAL	1571	100.0	64	100.0

Table 5.4 Composition of buildings according to wall cladding type in Mt Pleasant.

CHRISTCHURCH CENTRAL BUSINESS DISTRICT WALL CLADDING DATA				
CLASS	RESIDENTIAL		COMMERCIAL	
WALL CLADDING	NUMBER	PERCENTAGE	NUMBER	PERCENTAGE
brick	230	25.0	274	26.4
concrete	405	44.0	554	53.4
fibrolite	0	0.0	2	0.2
glass	0	0.0	2	0.2
iron	0	0.0	2	0.2
malthoid	0	0.0	1	0.1
mixture	0	0.0	105	10.1
roughcast	68	7.4	8	0.8
stone	0	0.0	3	0.3
wood	197	21.4	25	2.4
data missing	20	2.2	61	5.9
TOTAL	920	100.0	1037	100.0

Building age also plays a significant role in the performance of buildings during major earthquakes, particularly in the case of concrete and unreinforced masonry buildings. Spence e*t al.* (1998) report that two categories of non-domestic buildings that give rise to particular concern from a casualty point of view are: (1) pre-1935, unreinforced masonry buildings and (2) pre-1976, brittle concrete or steel buildings. In the Council property valuation database, building ages are in decades.

As well as considering the decade of construction and materials of construction, the vulnerability of buildings needs to be measured according to the number of storeys (Dowrick, 2003). The Council valuation data does not contain any information on building height. Building height is very important in modeling damage to structures following an earthquake (Dowrick, 2003). In this study, building heights were estimated by dividing the floor area of a building by its footprint. This yielded building heights classes of one and two-storey for residential buildings and 3 height classes (one-storey, two to three storeys and four or more storeys) for non-residential buildings.

Finally, the load bearing mechanism, decade of construction and building use information from the revised property valuation database were used to group the building data into four major building construction classes representing the buildings structural strength: un-reinforced masonry, timber frame, pre-1980 reinforced concrete and 1980-onwards reinforced concrete. These classifications have been adopted from the methodology used by Cousins (2004). The average response to earthquake shaking is assumed to be similar within each of these building classes. The revised building inventory was aggregated and maintained as two separate inventories: one for residential buildings and one for non-residential buildings. This enabled damage ratios describing the seismic performance of buildings in these two broad classes to be used to calculate losses. Furthermore, inference and classification rules in the GIS were used to infer missing data attributes and for assigning the classifications discussed above. Examples of two basic types of inference and classification rules are listed below.

1. Example rule for assigning building construction classification:

IF (date built < 1940 and wall cladding = brick)

***THEN** (construction class = unreinforced masonry)*

2. Example rule for inferring building occupancy:

IF (VNZ "use" category = lifestyle and number of storeys = 1)

***THEN** (building occupancy type = residential)*

The building construction types and their estimated proportions from the revised building inventory are given in Table 5.5 and Table 5.6. Table 5.7 gives the assumed building types and proportions used in a previous study for all of Christchurch by Cousins (2005a). It is important to note that the building proportions used in this study are quite different from those adopted by Cousins (2005a). The main reason for this difference is that the building proportions used by Cousins (2005a) were not based on building data for Christchurch but were derived from detailed information for Wellington City, with the only major difference being in the proportion of unreinforced masonry buildings, which for Wellington were 1 percent and 2 percent for residential and non-residential buildings respectively.

In contrast to the previous work done for Christchurch, the building inventory compiled in this study, enables an improved estimate of the building construction types.

Table 5.5 Building types and proportions adopted for the Christchurch CBD.

CBD	Fraction of Inventory (%)	
Construction Type	Residential	Non-residential
Unreinforced masonry	3	14
Pre-1980 reinforced concrete	20	30
1980 onwards reinforced concrete	24	20
Timber frame	53	36

Table 5.6 Building types and proportions adopted for Mt Pleasant.

Mount Pleasant	Fraction of Inventory (%)	
Construction Type	Residential	Non-residential
Unreinforced masonry	0	0
Pre-1980 reinforced concrete	2	10
1980 onwards reinforced concrete	24	70
Timber frame	74	20

Table 5.7 Building types and proportions adopted for Christchurch by Cousins (2005a).

Christchurch	Fraction of Inventory (%)	
Construction Type	Residential	Non-residential
Unreinforced masonry	2	5
Pre-1980 reinforced concrete	4	40
1980 onwards reinforced concrete	4	40
Timber frame	90	15

More detailed descriptions of the 4 construction types derived from Davey and Sheppard (1995), Stehle *et al*.(2002), Cousins (2004), Cousins (2005a) and Ventura *et al*. (2005) are given in the following sections.

1. UNREINFORCED MASONRY BUILDINGS

Unreinforced masonry buildings are reported to be particularly susceptible to earthquakes and are a key factor affecting how well or poorly an urban area will fare during an earthquake. They are considered to be the most hazardous form of construction in seismic areas. These types of structures can perform well if designed and constructed according to current building standards, but buildings which are old, decayed, of poor design or construction may perform very poorly in earthquakes. Damage is often severe enough to require demolition. Construction codes have been improved several times since the first was introduced to New Zealand in 1935. The 1980 era represents perhaps the greatest single step.

As mentioned earlier, building ages in the property valuation database are in decades. 1940 is the first decade after 1935. Therefore, in this study, structures with brick wall cladding type constructed prior to 1940 were classed as unreinforced masonry. Three percent of residential buildings and 14 percent of non-residential buildings in the Christchurch CBD fall into this category. On the other hand, no buildings in Mt Pleasant fall into this category.

2. TIMBER FRAME BUILDINGS

Timber framed buildings are the most common form of construction in New Zealand. These are typically single- or multiple-family dwellings or older, small commercial properties and are identified by brick veneer, timber and sometimes fibreboard cladding. Brick veneers, which can easily be confused with unreinforced masonry buildings, are more common for construction dating from the 1940 onwards. Timber-framed buildings are highly resistant to collapse because they are lightweight, although non-structural and contents damage can be significant. Age has a relatively minor impact on the fragility of timber-framed buildings.

53 percent of residential buildings and 36 percent of non-residential buildings fall into this category in the Christchurch CBD. 74 percent of residential buildings and 20 percent of non-residential buildings in Mt Pleasant are classed as timber frame.

3. CONCRETE BUILDINGS

This class includes concrete walls, concrete masonry, concrete frame and steel frame. Concrete buildings form a significant percentage of buildings in the study area. Concrete construction performs well when detailed to ensure continuity and ductility and if structural irregularities are avoided. Furthermore, age is highly significant for concrete buildings because there was a major improvement to the building codes in 1976, NZS4203:1976. All pre-1976 concrete buildings are included in the earthquake –prone buildings category, unless proven otherwise by engineering inspection. Building ages in the Council property valuation database are in decades. 1980 is the first decade after 1976. Hence, the data is divided into post 1980 and pre-1980 buildings.

A significant percentage of buildings in the Christchurch CBD fall into the pre-1980 category.

5.3 POPULATION DISTRIBUTION MODEL

Collapse of buildings due to ground shaking is widely believed to be the principal cause of earthquake casualties (Bird & Bommer, 2004). Therefore, in order to calculate casualties caused by building collapse due to earthquake ground shaking, it is important to allocate residents to individual buildings according to daytime and night-time building occupancy rates. This was done using the methodology adopted from Cousins (2004 & 2005a), where the building occupancy rates are calculated based on two primary building occupancy classes: residential and non-residential. This is of importance when the casualty rates depend on the type of building. The collapse rates of residential buildings are known to differ significantly from those of non-residential buildings (Dowrick, 2003).

Night-time populations for the whole study area were derived from the 2001 census usually resident population count. The census usually resident population is a count of all people who usually live in a given area, and are present in New Zealand, on a given census night. It excludes visitors from overseas and New Zealand residents who are temporarily overseas (http://www.stats.govt.nz). Second, an average occupancy rate (people per square metre of available floor area) was calculated, using the total population and the total floor area in the study region. That occupancy rate was applied to all the 75 data aggregation points. People were then allocated to each meshblock in proportion to the total floor area of the residential and non-residential buildings associated with it. Finally, an assessment was made between residential buildings, non-residential buildings and outdoors at 11am and at 2am using the location factors as per Table 5.8. At any time of the day some people are indoors at the place of work, some are indoors at home, and some are outdoors. The term “non-residential” in the event of loss calculation means “not at home”. Hence, it includes shoppers, students, hospital patients, etc. (Cousins, 2004).

Table 5.8 Assumed locations of people for daytime and night-time earthquake scenarios (adopted from Cousins, 2005a).

Location of people	Time of occurrence	
	11am (workday)	2am (night-time)
In residential buildings	22%	95%
In non-residential buildings	58%	4%
outdoors	20%	1%

A previous study of casualties for earthquakes on the Wellington fault (Spence *et al*., 1998) has assumed similar night-time and daytime allocations of people. The daytime allocations, however, were somewhat different from those of Table 5.8, being 28 percent to residential buildings, 51 percent to non-residential buildings and 21 percent to outdoors. This is because the percentages used by Spence *et al.* (1998) were adopted from findings in non- New Zealand cities.

The resulting spatial distribution of the daytime and night-time populations in the Christchurch CBD and Mount Pleasant are shown in Figures 5.10 to 5.17.

5.4 SUMMARY

This chapter demonstrated the methodology of compiling an inventory at the census meshblock level. For each meshblock within the study area, the final inventory comprises the following information: total floor area, replacement values; building construction material; occupancy types; number of occupants, at two different times of the day; estimated heights; and decade of construction. Finally, the use of a GIS allowed for easy processing, manipulation and analysis of the large data sets.

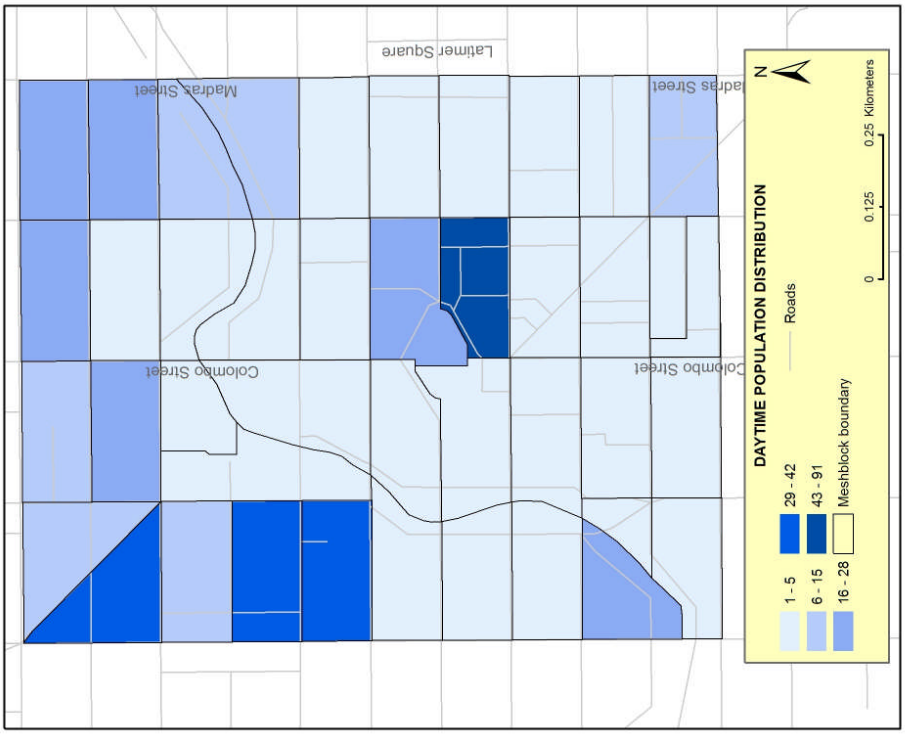

Figure 5.10 Map of daytime residential population distribution by meshblock in the Christchurch CBD

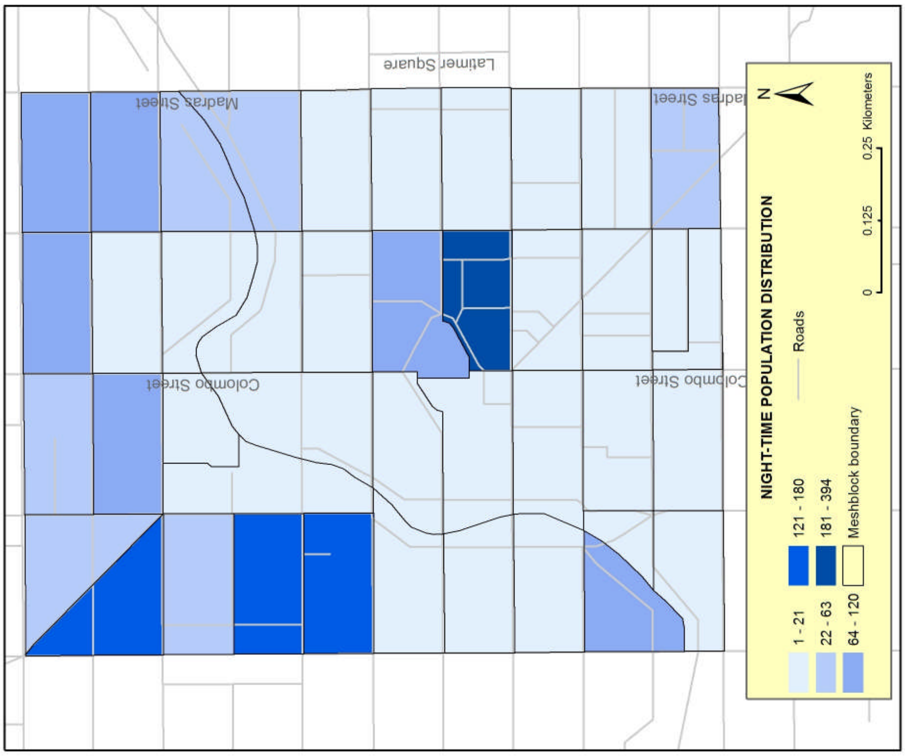

Figure 5.11 Map of night-time residential population distribution by meshblock in the Christchurch CBD.

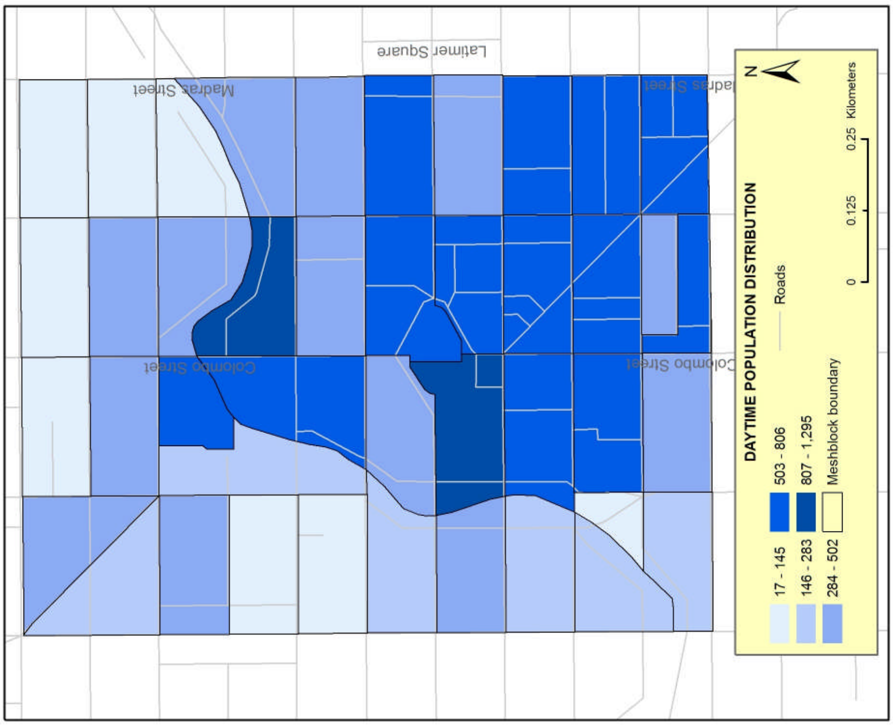

Figure 5.12 Map of daytime non-residential population distribution by meshblock in the CBD.

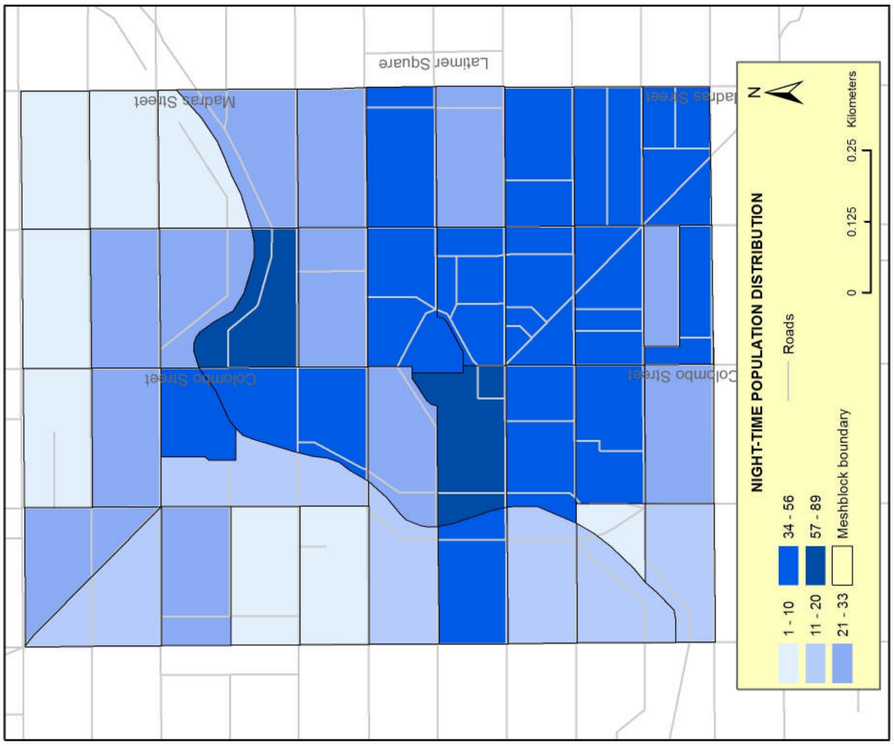

Figure 5.13 Map of night-time non-residential population distribution by meshblock in the CBD.

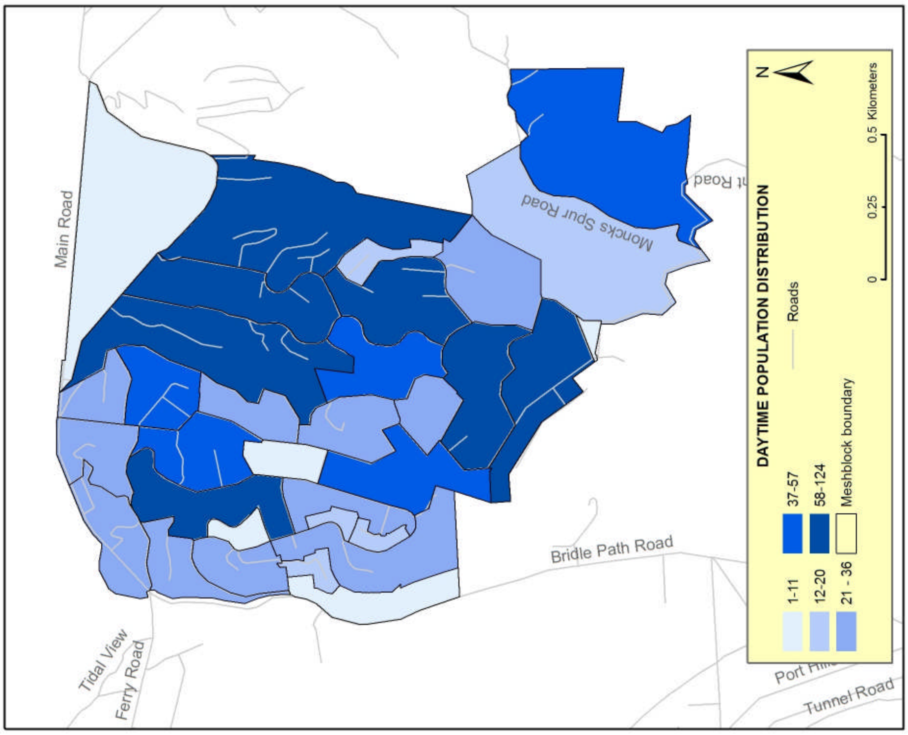

Figure 5.14 Map of daytime residential population distribution by meshblock in Mt Pleasant.

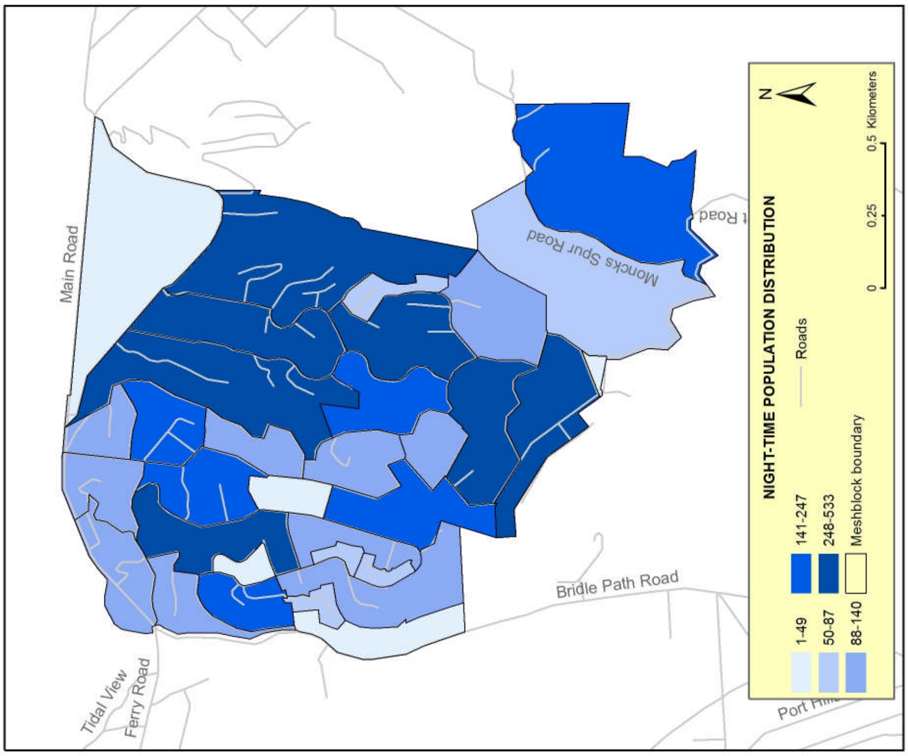

Figure 5.15 Map of night-time residential population distribution by meshblock in Mt Pleasant.

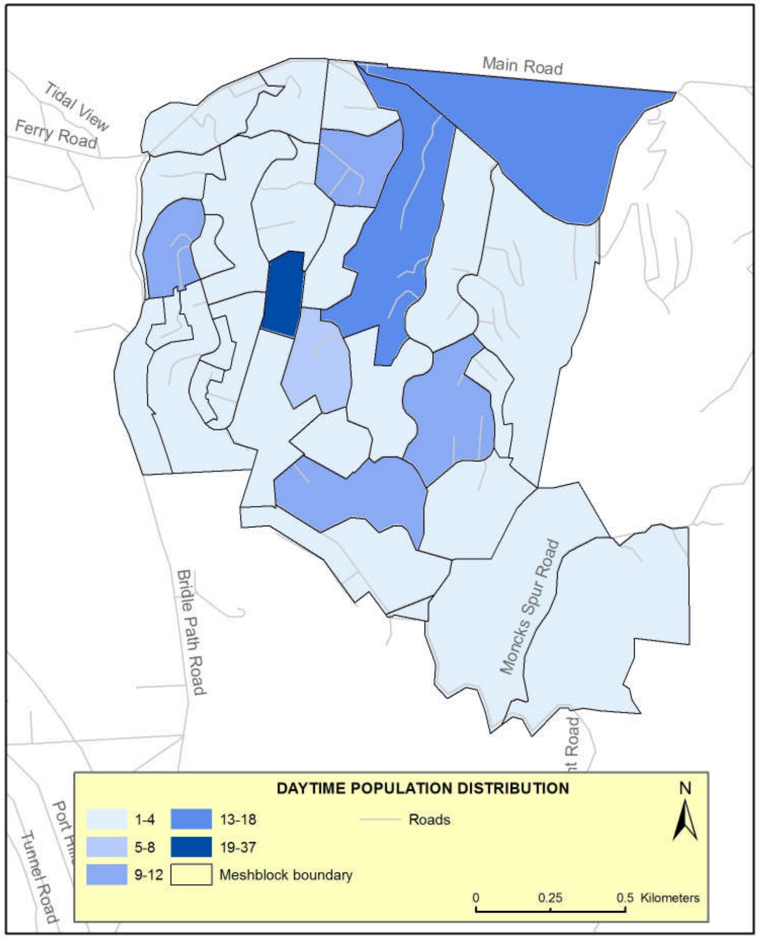

Figure 5.16 Map of daytime non-residential population distribution by meshblock in Mt Pleasant.

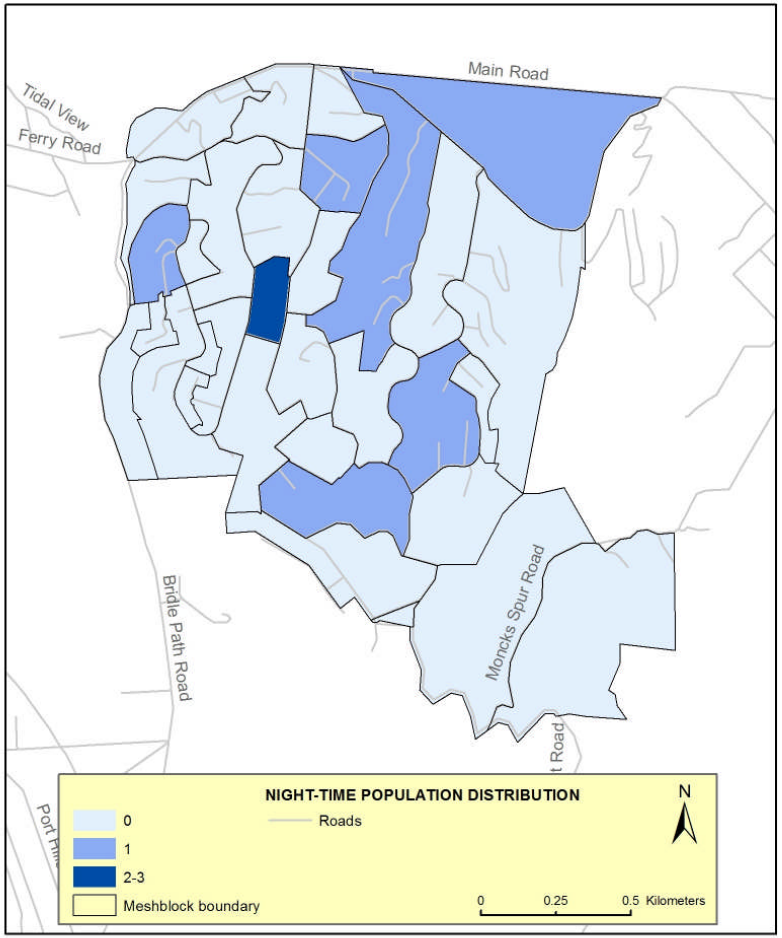

Figure 5.17 Map of night-time non-residential population distribution by meshblock in Mt Pleasant.

CHAPTER 6

CHRISTCHURCH SEISMIC RISK ASSESSMENT-

DAMAGE AND LOSS MODELLING

6.1 INTRODUCTION

The final steps in a seismic risk assessment study are damage modelling and loss estimation. This chapter documents the damage and loss estimation methodologies, which use the three component models (seismic hazard, building inventory and population distribution) from Chapters 4 and 5 as inputs to derive damage and loss estimates. First, derivation of damage ratios, which relate the earthquake ground shaking in terms of the Modified Mercalli Intensity (MMI) to a given building construction class is outlined followed by a discussion on the economic loss, building collapse and casualty models. The damage ratios are used in the building collapse model to estimate direct damage to the building inventory, which serves as inputs to the economic loss model. The outputs of the building collapse model and the population distribution characteristics serve as inputs to the casualty model. Losses are quantified in terms of direct economic loss and casualties only. Loss estimation is a very important part of risk estimation because the estimates of dollar losses and casualties are easier to comprehend than the terms used to quantify damage.

The components of the seismic risk assessment methodology which are discussed in this chapter are highlighted in Figure 6.1.

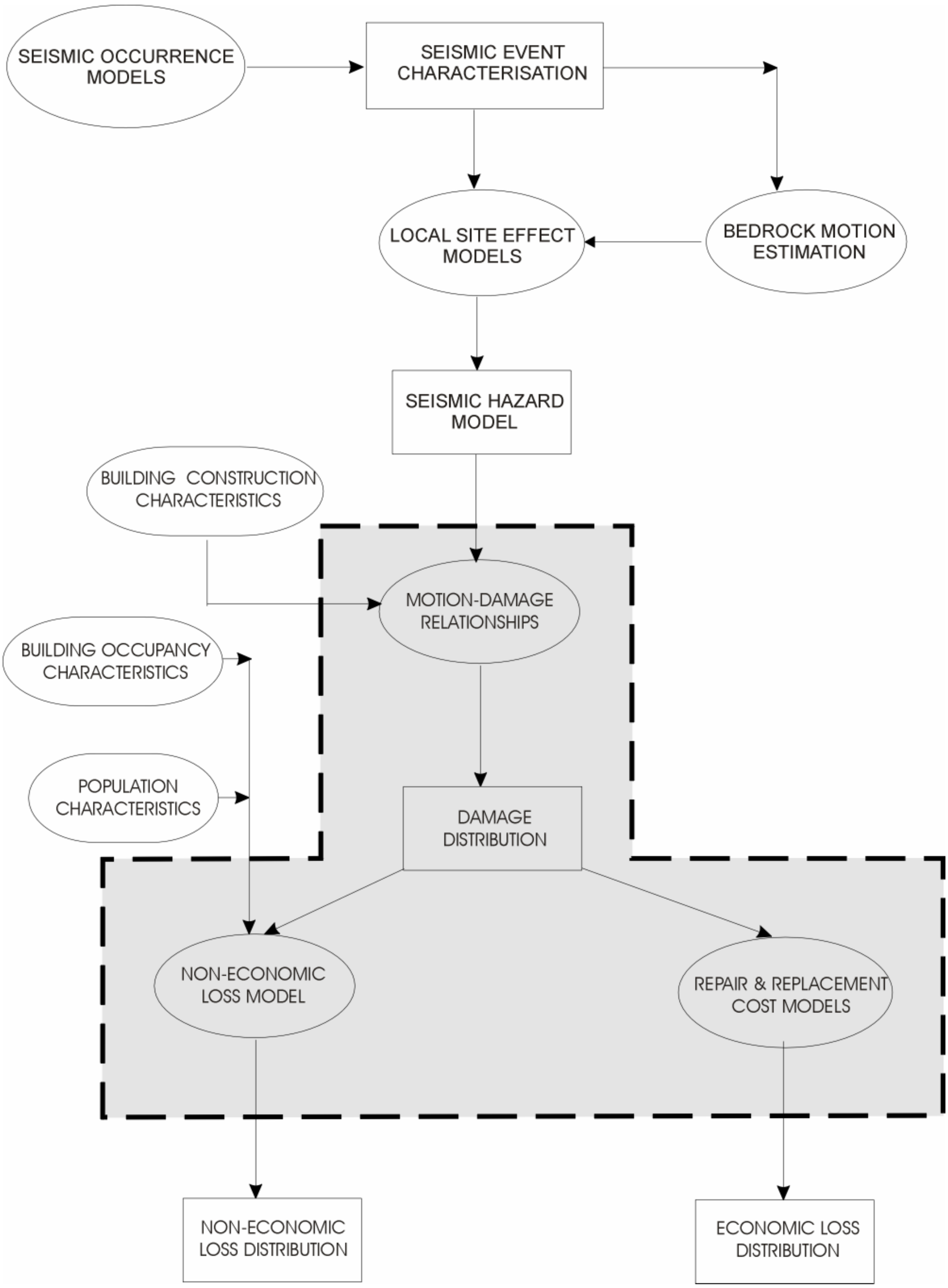

Figure 6.1 Components of a seismic risk assessment methodology. The highlighted components are those which are discussed in this chapter (modified after King & Kiremidjian, 1994).

6.2 BUILDING DAMAGE AND LOSS MODELLING

Building damage resulting from earthquake ground shaking is an area of ongoing research. During the 1970s, the National Oceanic and Atmospheric Administration (NOAA) and the United States Geological Survey (USGS) assembled teams of experts, predominantly engineering consultants and federal government geoscientists, who produced large-scale loss studies that set the basic pattern for scope and methods of others to follow (FEMA, 1989).

The damage and loss estimation methodologies used in this study are essentially that of Cousins (2004). This method has been shaped by previous New Zealand-based earthquake damage and loss studies (Dowrick, 1991a; Dowrick & Rhoades, 1993, 1995; Dowrick *et al.*, 1995b; Dowrick, 1998; Dowrick *et al.*, 1998; Spence *et al.*, 1998; Cousins & Heron, 2000; Dowrick *et al.*, 2001).

Cousins' (2004) model can run both probabilistic and deterministic damage and loss scenarios and is based on the Modified Mercalli Intensity (MMI) scale. In this study, a deterministic seismic risk assessment model was used. Deterministic models involve defining specific events and computing the damage and loss associated with that particular event, whereas a probabilistic model computes damage and loss for different events, accounting for the probability of each event.

Cousins' (2004) methodology is one of many studies that have used the MMI scale to quantify building damage given the level of ground shaking. The Applied Technology Council project, ATC-13 is a benchmark study that uses MMI to measure the level of ground shaking (Rojahn & Sharpe, 1985). Other well-known examples of overseas studies that use this shaking characterisation include Algermissen *et al.* (1972), ATC (1991), ATC (1992), Whitman *et al.* (1973), Whitman *et al*. (1997) and Wiggins (1981). Rojahn (1994) reports that the principal reason that MMI data is quite commonly used is due to the large amount of the available data on earthquake effects being available in this form. In addition, an important positive feature of the MMI scale is that intensity ratings are also based on other phenomena that have a more universal and unvarying basis. These include such items as toppling of grocery-shelved items at low intensity levels, ground failures at intermediate intensities, and the disorientation of persons at high shaking intensities. Furthermore, Musson (2000) states that the advantage of using intensity for risk studies is that it bypasses the problems associated with relating damage to physical measures of ground motion.

It is widely acknowledged (Davey, 1994; King & Kiremidjian, 1994; Rojahn, 1994; Kircher *et al.*, 1997), however, that the MMI scale has several drawbacks that make it less than ideal for earthquake loss studies for large urban areas. The shortcomings include:

1) The scale is subjective in nature and can be interpreted differently by different users;
2) The scale is not quite so suitable for new types of construction as it is based largely on the performance of unreinforced masonry buildings and chimneys and other types of older construction; and
3) The scale combines long and short period structural damage at given intensity levels and is therefore biased by earthquake magnitude and distance.

For these reasons, there has been an effort in current research to use ground motion parameters such as peak ground accelerations (PGA) and spectral response to quantify ground shaking(Whitman *et al.*, 1997). This approach bypasses the need to evaluate the intensity of ground shaking at sites and avoids difficulties in using MMI.

6.3 DERIVATION OF DAMAGE RATIOS

The first step in damage modelling is to derive quantitative measures of the vulnerability of the elements at risk (buildings and population) to the hazard (ground shaking). This is done in terms of a damage ratio (D_r) defined as:

$$\mathbf{D_r} = \frac{\textbf{Repair cost of building}}{\textbf{Replacement value of building}}$$

Here, D_r is a function of intensity and the physical nature of the building considered (Dowrick, 2003). The population of property items for any given distribution of D_r is drawn from the area between two adjacent isoseismals, so that the MM6 intensity zone (for example) is defined as the area between the MM6 and MM7 isoseismals (Figure 6.2).

In this study, the damage ratio is defined as the cost of repairing an earthquake damaged building divided by the replacement cost of the building at risk. The repair costs comprise costs to repair both structural damage and non-structural damage to a building and the cost to restore the building to the condition it was in before the earthquake. Structural repairs relate to the load-bearing elements of the building. Non-structural elements include ceilings, pipes, etc. These calculations do not include building contents. The building replacement value, on the other hand, is the cost of replacing the building with a new building having the same floor area, function, standard of finishes and services using modern materials and construction methods. It also excludes building contents.

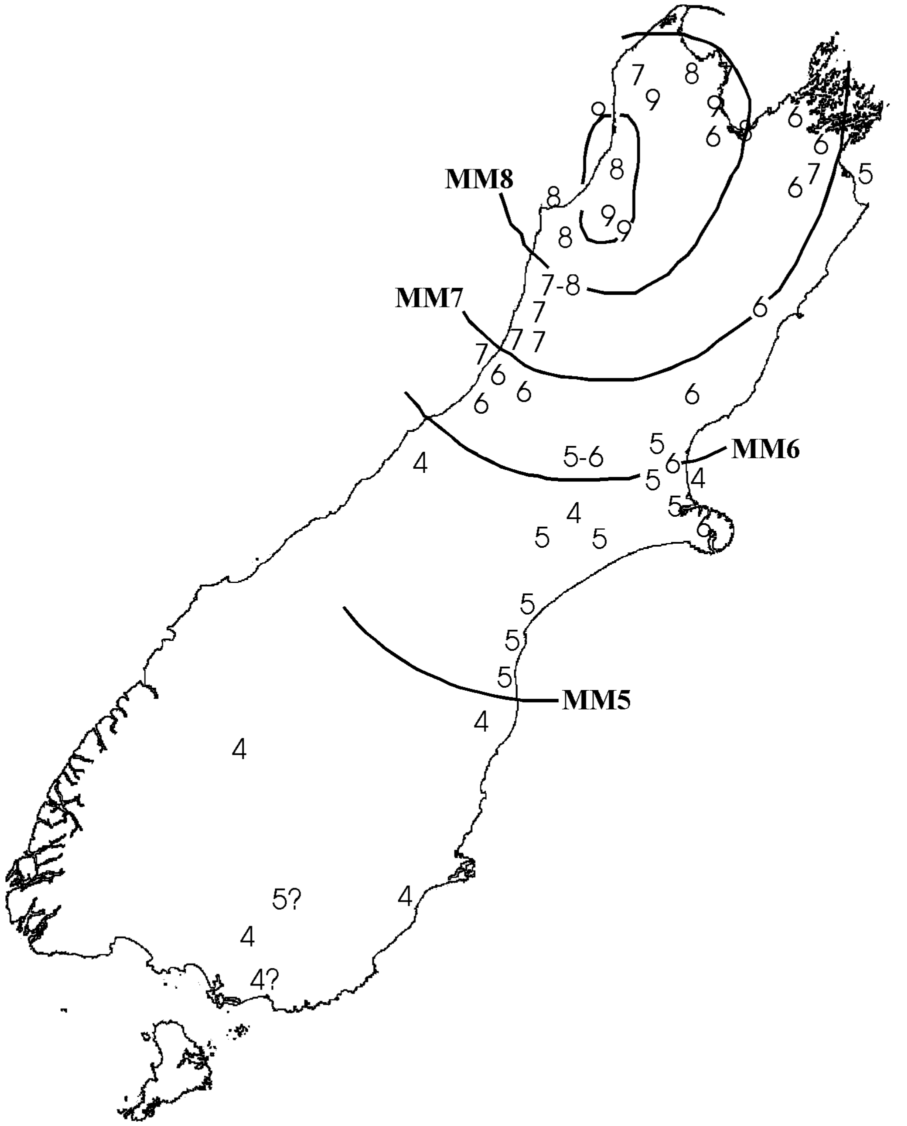

Figure 6.2 Map showing a typical example of Modified Mercalli intensity isoseismals, using data from the magnitude 7.7 Murchison (Buller) earthquake of 1929. An intensity zone is the area between two adjacent isoseismals, e.g. the MM6 zone is the area between the MM6 and MM7 isoseismals (Cousins, 2005a).

Replacement cost is used rather than the market value of the buildings because disaster assistance and most insurances are based on replacement cost. Market value is not constant in relation to replacement cost. For example, typical estimates of market value include lot value, which is not included in the replacement cost of a building and may cause market value to largely surpass replacement cost (Kircher *et al.*, 1997).

The damage ratios used in this model were derived from a number of sources. Most were derived using the damage ratios estimated by Dowrick and colleagues (Dowrick, 1991b; Dowrick *et al.*, 1995a; Dowrick & Rhoades, 1997; Rhoades & Dowrick, 1999) in recent studies of the following New Zealand earthquakes:

1) 1931 M_w 7.8 Hawke's Bay
2) 1942 M_w 7.1 Wairarapa
3) 1968 M_w 7.2 Inangahua
4) 1987 M_w 6.5 Edgecumbe

In the case of the 1931 Hawke's Bay earthquake, Dowrick's (1991a) study was the first to have ever been conducted that quantified damage in the MM10 zone of an earthquake, for any class of construction. For the 1968 Inangahua earthquake, Dowrick *et al.* (2001) evaluated the vulnerability of domestic property for six intensity zones, from MM5 to MM10 inclusive. This was also the first time that the vulnerability of any class of building and the effect of brittle chimneys on damage levels was examined in so many intensity zones. Furthermore, for the 1987 Edgecumbe earthquake, Dowrick and Rhoades (1990; 1993) gave the expected damage distribution for a number of forms of construction at the MM7 and MM9 intensity levels. In the above studies, great care was taken to account for not only the repair costs but also the replacement value of all property items, damaged as well as undamaged. The in-depth assessment of the performance of buildings and their contents during these four earthquake events can be considered ground-breaking in terms of improving the reliability of risk forecasting in New Zealand.

Damage ratios for building types not represented in the New Zealand datasets were estimated using a set of subjective estimates made for Californian buildings in the Applied Technology Council publication, ATC-13. This report contains damage ratios for over 70 different classes of buildings and infrastructure asset types put together by an advisory panel of 71 specialists in earthquake engineering. Although, the ATC-13 report was initially developed for buildings in California, it has become a basis for damage estimation elsewhere around the world and has been frequently used in other regions with adjustments for the area under study.

Cousins and Heron (2000) state that the use of ATC-13 as a source of data on damage ratios has its drawbacks as well. The reasons for this are:

1) The ATC-13 data were based totally on subjective judgement of professional engineers who had drawn on their experience history and very limited data;
2) Some of the classes of assets covered in the report can possibly contain items that have different levels of resistance to earthquake damage; and
3) ATC-13 estimates of damage ratios, at shaking intensities between MM6 and MM8 appear to be pessimistic.

Furthermore, Cousins and Heron (2000) argue that the Dowrick damage ratios are more reliable than those of ATC-13, but the ATC-13 estimates cover a much wider range of asset types. Both sources give relatively similar values for commercial and domestic buildings at an intensity of MM9 and so the MM9 values were used as benchmarks. The "Dowrick" results were then used to define the variation of damage ratio with intensity and the ATC-13 results were used to differentiate between the various types of buildings. The Dowrick and ATC-13 damage ratios are compared in Figures 6.3 to 6.6.

For modelling purposes, the overall damage distribution was assumed to be defined by the mean damage ratio as a function of intensity level as follows:

$$\overline{D_r} = A \times 10^{\left(\frac{B}{MMI - C}\right)}$$

Where, D_r is the mean damage ratio for a large population of buildings of a given class, MMI the shaking intensity and A, B and C are constants (Cousins, 2004).

Mean damage ratios are used because they are average factors for all buildings of a given class. They do not give the distribution of damage, such as how many buildings had little or no damage or how many had moderate damage. The mean damage ratio directly defines property loss but does not directly indicate number of casualties.

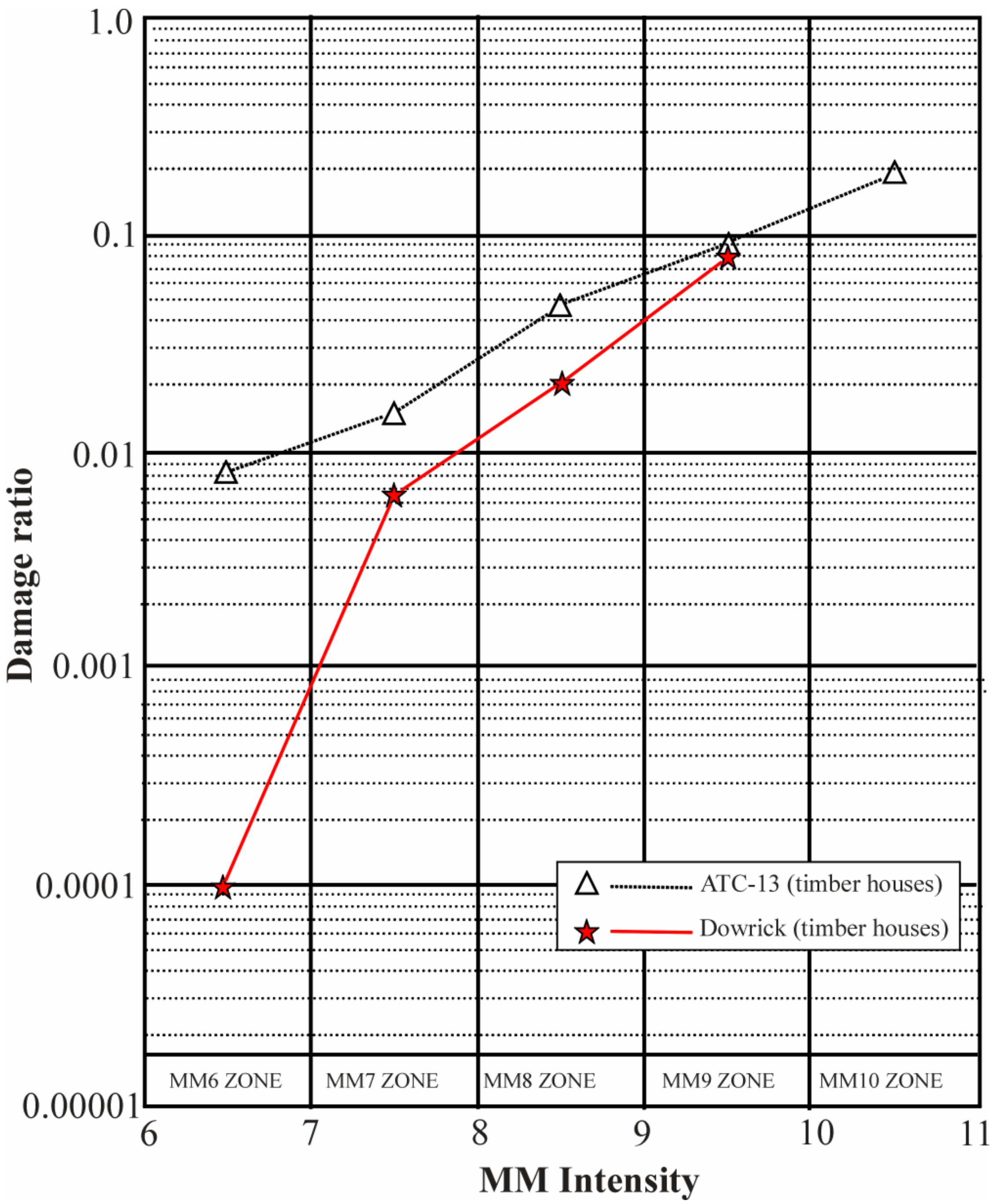

Figure 6.3 Comparison of published Dowrick and ATC-13 damage ratios for timber houses. The Dowrick estimates were considered more reliable of the two because they are based on actual losses from a New Zealand earthquake (Cousins & Heron, 2000).

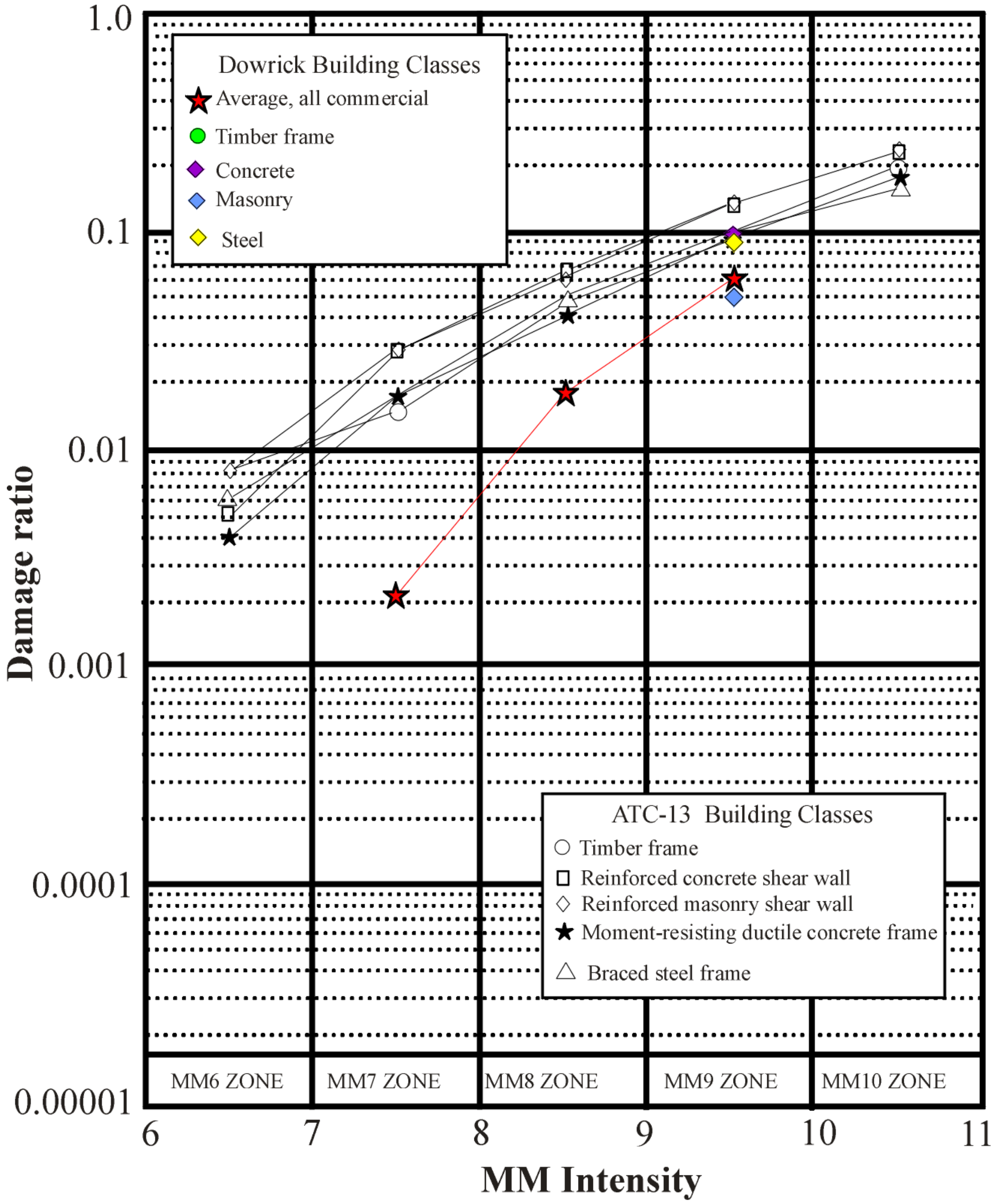

Figure 6.4 Comparison of published Dowrick and ATC-13 damage ratios for commercial buildings. The Dowrick estimates were considered more reliable of the two because they are based on actual losses from a New Zealand earthquake (Cousins & Heron, 2000).

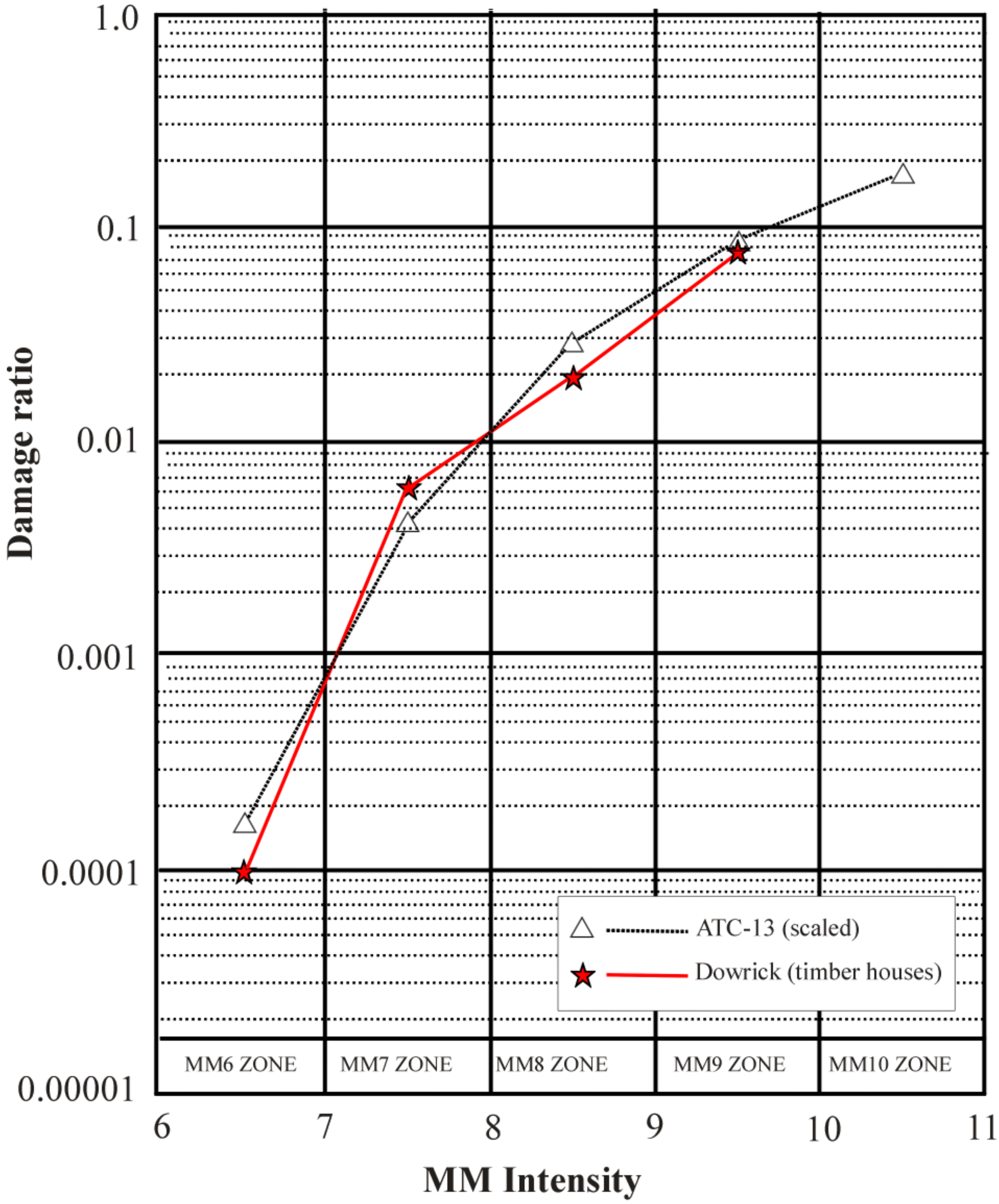

Figure 6.5 Comparison of estimated Dowrick and ATC-13 damage ratios for timber framed houses. The agreement is good (Cousins & Heron, 2000).

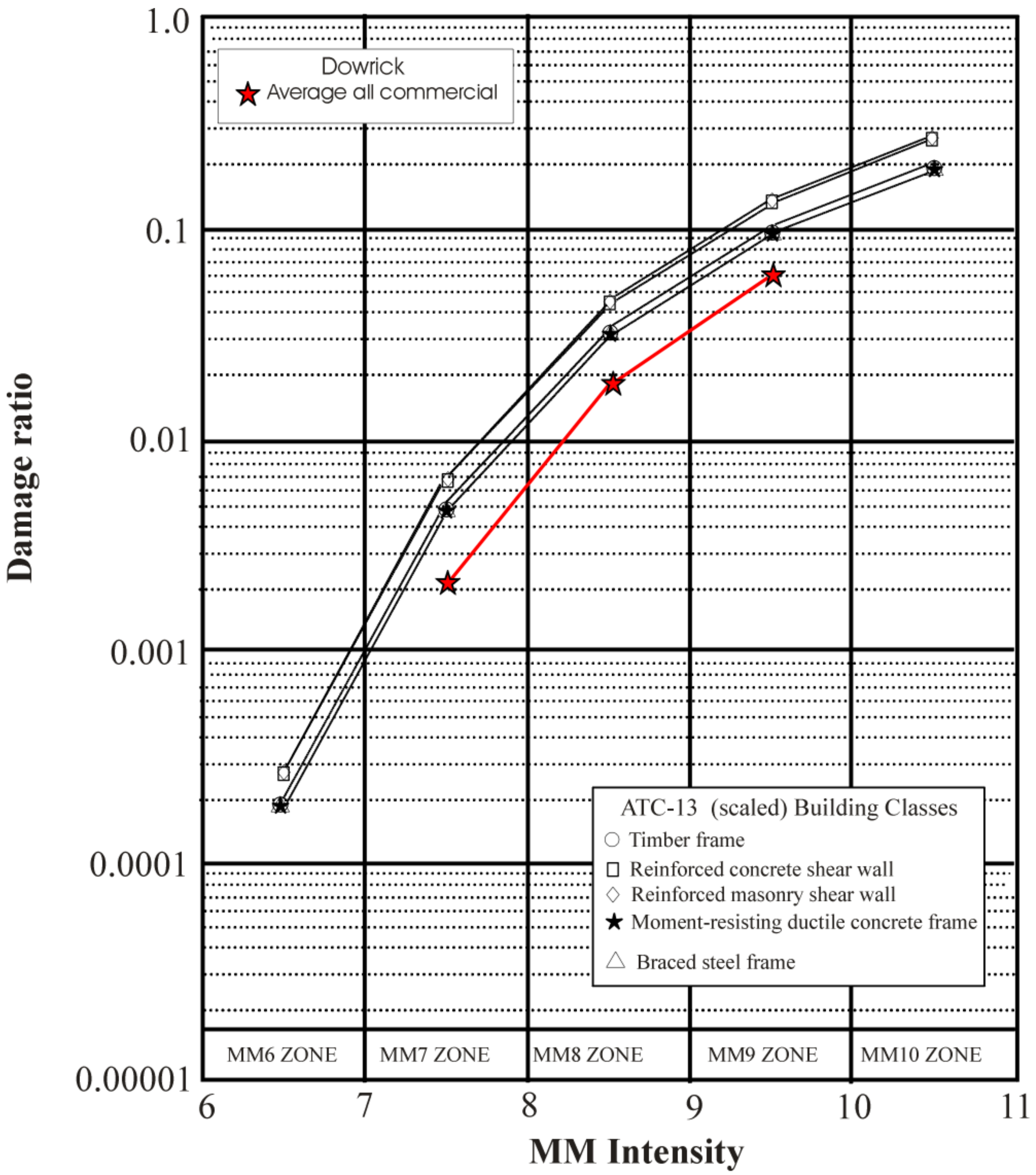

Figure 6.6 Comparison of estimated Dowrick and ATC-13 damage ratios for commercial buildings. The agreement in trend is good (Cousins & Heron, 2000).

The relative vulnerabilities of the four classes of buildings based on the New Zealand and Californian experiences are listed in Table 6.1.

Table 6.1 Relative fragilities assigned to various categories of buildings (from Cousins, 2004).

Construction Type	Age	Height	Use	Relative Fragility
URM (unreinforced masonry)	All ages	All heights	All uses	5.4
Timber frame	All ages	All heights	Residential	1.4
			Non-residential	1.2
Pre-1980 reinforced concrete	All ages	All heights	All uses	2.3
Post-1980 reinforced concrete	All ages	All heights	All uses	1.0

Finally, the estimates of mean damage ratios were converted to expected direct economic losses as follows:

$$\textbf{Loss} = \Sigma\ (D_{r,i}\ \textbf{x}\ \textbf{Replacement Value}_i),$$

Where, $D_{r,i}$ is the mean damage ratio for asset item "i". The functions used for estimating potential earthquake losses to buildings are shown in Figure 6.7.

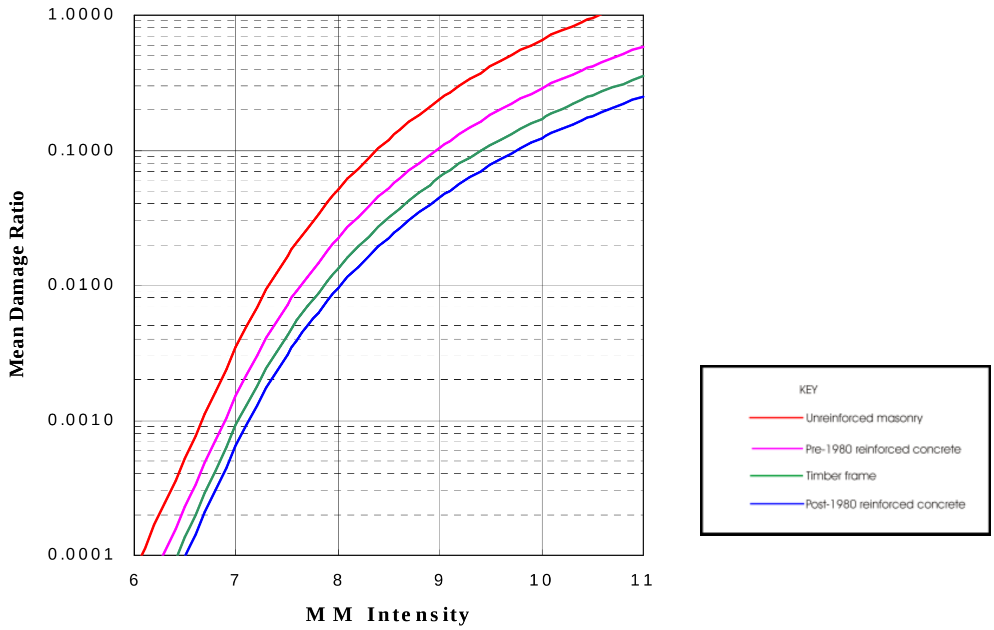

Figure 6.7 Representative mean damage ratios for buildings in Christchurch (Cousins, J. pers comm.2006).

6.4 BUILDING COLLAPSE MODEL

New Zealand statistics on collapse are insufficient to offer a satisfactory basis for the assessment of the proportion of collapsed buildings at each mean damage ratio level. Hence, collapse probabilities for each building class were derived using loss data gathered during various New Zealand earthquakes modified and extended by data from foreign earthquakes, where construction was similar (Spence *et al.*, 1998).

In this study, the average relationship (Figure 6.8) between mean damage ratios and the proportion of collapsed building for the four buildings classes was defined as:

$$\overline{C_r} = \mathrm{A} \times 10^{\left(\frac{\mathrm{B}}{\mathrm{MMI - C}}\right)}$$

Where $\overline{C_r}$ is the mean collapse rate, MMI the shaking intensity, and A, B and C are constants (Cousins, 2004).

Cousins (2004) reports that the loss of volume of the building is the key factor that determines number of casualties, with a loss of 50 percent being the level at which significant numbers of casualties begin to occur. Therefore, in this study, “collapse” is defined as being a volume loss of 50 percent or more.

Thiel *et al.* (1987) compiled data on earthquake damage from a variety of sources that indicates the usefulness of hard data about past performance in studies that attempt to estimate future performance. However, for many types of buildings, and especially for those in areas that have experienced few if any damaging earthquakes, actual data are very sparse or nonexistent. For such buildings, it is necessary to rely on expert opinion.

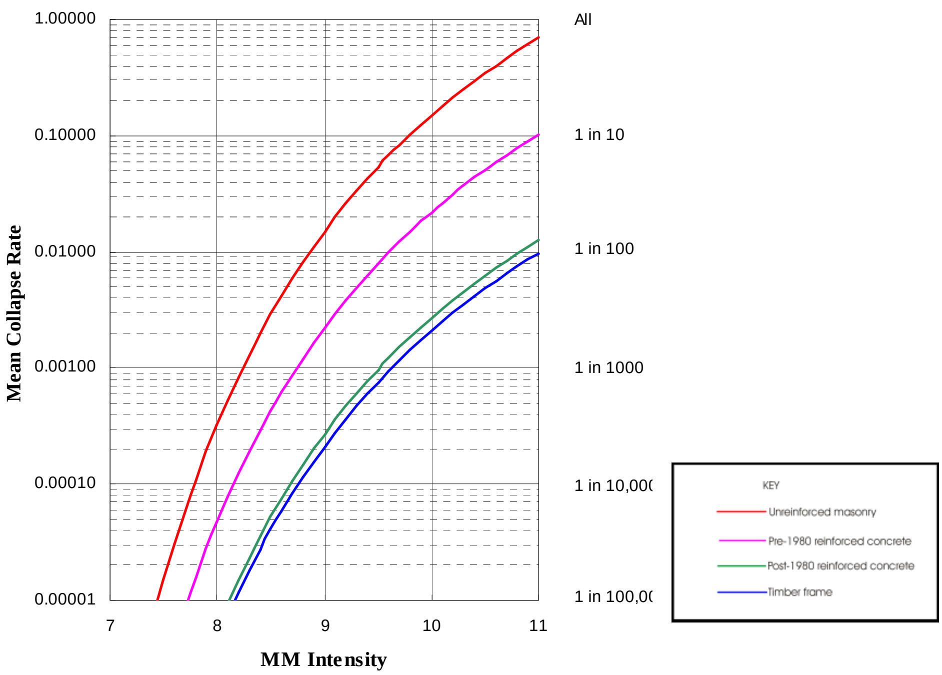

Figure 6. 8 Mean collapse rates for the classes of building used in the earthquake loss model (Cousins, J. pers comm.2006).

6.5 CASUALTY MODEL

The estimation of casualties due to structural damage caused by an earthquake is a complex area of study even though deaths and injuries are possibly the most crucial of all the losses to be calculated. Unfortunately, the ability to calculate expected rates of casualties is not as good as in the case of property loss. The available literature contains less information on earthquake casualties than on building and other damage.

Initially, rather than relating casualties directly to damage or property loss estimates, most large-scale studies used citywide (or larger) casualty statistics from previous earthquakes for casualty estimation. One such example is the early National Oceanic and Atmospheric Association (NOAA) studies (FEMA, 1989) which used historical casualty rates per unit of population for wood frame dwellings and estimated rates for other types of construction, or used citywide casualty rates from previous earthquakes applied to the population as a whole, adjusted up or down based on changes in construction practice. These estimates were in effect crude extrapolations of the limited data available, primarily from Californian earthquakes (FEMA, 1989).

In more recent studies though, the tendency has been to relate casualties to levels of damage (Whitman *et al.,* 1997; Kircher *et al.,* 1997; Spence *et al.,* 1998; Cousins *et al.,* 2000) which is thought to yield more reliable estimates. These casualty estimation models calculate a probable number of dead and/or injured by modelling the number of collapsed structures expected within an inventory of buildings, an expected average number of persons per structure, expected death rates and injury ratios.

The casualty estimation methodology adopted for this study is that of Cousins (2004) which was essentially moulded by the methodology of Spence *et al*. (1998) where casualty rates (Table 6.2) were derived from major earthquakes affecting central New Zealand. This model uses the inputs from the building collapse model with building inventory and population data to quantify casualties. A direct relationship is assumed between structural damage and casualties. Hence, the numbers of casualties are proportional to the numbers of collapsed buildings. Furthermore, the methodology estimates casualties in residential and non-residential buildings, both at night-time and daytime, caused directly from building collapse only. Excluded are casualties due to infrastructure collapse (e.g. bridges) as well as indirect casualties due to heart attacks, psychological effects or injuries suffered post earthquake (e.g diseases or due to clean-up activities).

The casualties were divided into three categories: dead, seriously injured and moderately injured. A serious injury is defined as one that will result in death if the person does not get prompt medical or surgical treatment. A moderate injury is defined as one that is not immediately life threatening but requires medical or surgical treatment (Cousins, 2004).

Table 6.2 Proportions of occupants killed or injured in buildings that collapse (from Cousins, 2004).

Building Use	Kill Rate	Serious Injury Rate	Moderate Injury Rate
Non-residential	0.20	0.04	0.12
Residential	0.01	0.005	0.10

6.6 SUMMARY

The methodologies used herein enabled the estimation of direct building damage due to earthquake ground shaking and resultant economic loss and casualties. Identifying the relationship between the intensity of ground shaking and the damage experienced by a certain building class, is essential to damage and loss modelling. Due to the lack of data from past earthquakes in New Zealand, relatively little is known concerning the earthquake vulnerability of buildings and resultant casualty numbers. To deal with the lack of information, the damage and loss estimation methodologies used in this study are based on international and national data as well as expert opinion.

CHAPTER 7

CHRISTCHURCH SEISMIC RISK ASSESSMENT – RESULTS

7.1 INTRODUCTION

This chapter presents the loss estimation results obtained by running the seismic risk assessment component models discussed in the preceding chapters. A GIS was used to map the distribution of loss due to the two earthquake scenarios. First, the estimated economic loss due to building damage is presented followed by a discussion on predicted casualty numbers.

7.2 ECONOMIC LOSS

Tables 7.1 and 7.2 summarise the results of the loss modelling. Buildings are divided into two broad classes, residential and non-residential. Table 7.1 presents the calculated economic losses due to building damage in the Christchurch CBD in the two scenario earthquakes. Total estimated losses resulting from scenario 1 and scenario 2 earthquakes total $5.4 million and $33.3 million respectively. It is important to note that total losses due to a scenario 2 earthquake are approximately 6 times those resulting from a scenario 1 earthquake. A comparison of the total losses with the replacement value of the buildings indicates that losses due to a scenario 1 earthquake amount to only 0.3 percent of the building stock replacement value while losses due to a scenario 2 event amount to approximately 2 percent of the building stock replacement value.

Table 7.1 Summary of economic loss predictions for a Scenario 1 and Scenario 2 earthquake in the Christchurch CBD.

CHRISTCHURCH CBD

Scenario 1: Alpine fault earthquake (Milford_Haupiri, segment 4)
Magnitude at source: 8.10
Depth: 6km
MMI (max): 7.3
MMI (min): 6.4
Epicentral distance: approx. 135 km

Scenario 2 : Ashley Fault Earthquake
Magnitude at source: 7.2
Depth: 7.5km
MMI (max): 8.3
MMI (min): 7.0
Epicentral distance : approx. 45 km

Building Class	Number of Buildings	Total Floor Area (m^2)	Replacement Value ($)	Scenario 1 Loss ($)	Scenario 2 Loss ($)
Residential	920	111,880	234,000,000	530,000	3,300,000
Non-residential	1,037	1,047,667	1,660, 000,000	4,900,000	30,000,000
Total	**1957**	**1,159,547**	**1,894,000,000**	**5,430,000**	**33,300,000**

Table 7.2 Summary of economic loss predictions for a Scenario 1 and Scenario 2 earthquake in Mount Pleasant.

MOUNT PLEASANT

Scenario 1: Alpine fault earthquake (Milford_Haupiri, segment 4)
Magnitude at source: 8.10
Depth: 6km
MMI (max): 7.3
MMI (min): 6.4
Epicentral distance : approx. 143 km

Scenario 2 : Ashley Fault Earthquake
Magnitude at source: 7.2
Depth: 7.5km
MMI (max): 8.3
MMI (min): 7.0
Epicentral distance : approx. 52 km

Building Class	Number of Buildings	Total Floor Area (m^2)	Replacement Value ($)	Scenario 1 Loss ($)	Scenario 2 Loss ($)
Residential	1571	330,969	632,000,000	160,000	1,900,000
Non-residential	64	7,812	14,500,000	7,300	64,000
Total	**1635**	**338,781**	**646,500,000**	**167,300**	**1,964,000**

Table 7.2 presents the calculated losses to buildings in Mount Pleasant due to the two scenario earthquakes. The results suggest that the suburb of Mount Pleasant will suffer a total estimated loss of approximately $0.2 million in a scenario 1 earthquake. This amounts to approximately 0.03 percent of the building stock replacement value. This low total is mainly due to the very low losses to both building classes. In the case of a scenario 2 earthquake, Mount Pleasant would sustain total estimated losses equalling approximately $2 million, which amounts to 0.3 percent of the building stock replacement value. As a result, total losses due to a scenario 2 earthquake are 10 times those resulting from a scenario 1 earthquake.

Economic losses resulting from a scenario 2 earthquake exceed those resulting from scenario 1 because, in this study, loss due to building damage is modelled as a direct function of the intensity of earthquake ground shaking. The prevailing intensity of ground shaking in scenario 2 is near MM8 and MM7 in scenario 1. Buildings are therefore exposed to higher intensities of shaking in a scenario 2 event, which consequently result in greater damage and losses. Figure 7.1 illustrates the distribution of economic losses by building class for both scenario earthquakes in the two study areas.

It is evident from Figure 7.1, that the greatest economic loss by building class will be sustained by non-residential buildings in the Christchurch CBD. In both scenarios, losses to non-residential buildings in the CBD constitute 90 percent of the total loss incurred. On the other hand, the non-residential buildings in Mount Pleasant are relatively unscathed and contribute to only 4 percent of the total loss. Furthermore, an interesting feature to note is that greater damage will be sustained by the residential buildings in the CBD than the residential buildings in Mount Pleasant in both scenario earthquakes, although there are twice as many residential buildings in Mount Pleasant.

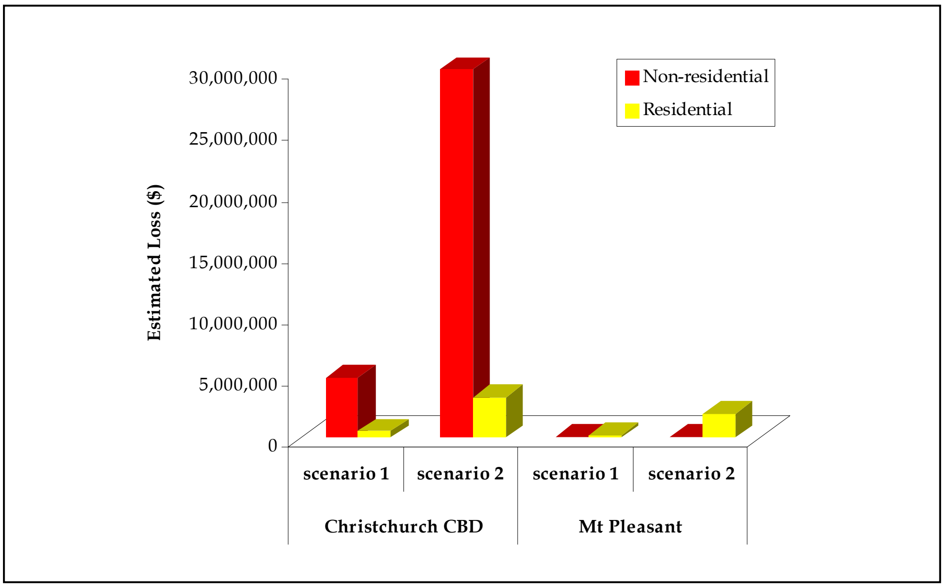

Figure 7.1 Distribution of economic loss according to building occupancy class in both earthquake scenarios.

In both earthquake scenarios, losses incurred by non-residential buildings constitutes on average 87 percent of the total loss incurred. This is partly because non-residential buildings comprise a large proportion of the total building stock, both in terms of numbers and value. Additional factors that could possibly be contributing to the differences in loss estimates observed amongst the study areas and also between different building occupancy classes are: (1) the building construction type; and (2) the era of construction. First, 14 percent of the non-residential building stock in the CBD comprises unreinforced masonry construction (Figure 7.2). Second, an estimated 9 percent of the total building stock in the CBD (Figure 7.3) is comprised of unreinforced masonry buildings as opposed to none in Mount Pleasant. Unreinforced masonry buildings are known to be the most vulnerable to earthquake ground shaking. Studies (Dhu & Jones, 2002; Dowrick, 2003) have shown that they are twice as likely to suffer damage as any other building type. Predictably, unreinforced masonry buildings have the highest mean damage ratios. This consequently results in high losses. Furthermore, an estimated 25 percent of the building stock in the CBD were classed as Pre-1980 reinforced concrete as opposed to only 6 percent in Mount Pleasant (Figure 7.3). This also results in higher observed losses in the CBD because Pre-1980 reinforced concrete buildings have higher mean damage ratios relative to timber frame and Post-1980 reinforced concrete buildings.

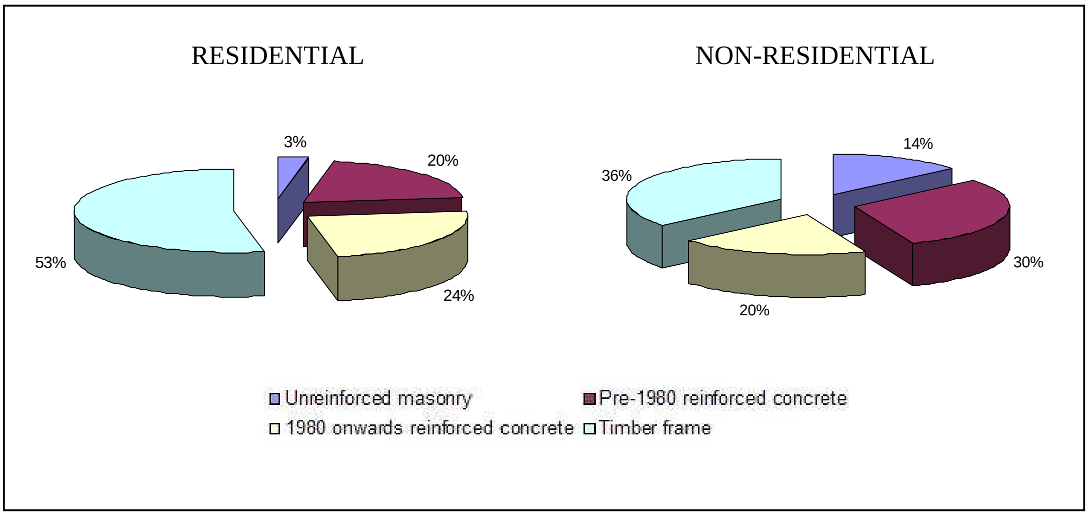

Figure 7.2 Estimated proportions of building construction types within the residential and non-residential building stock in the Christchurch CBD.

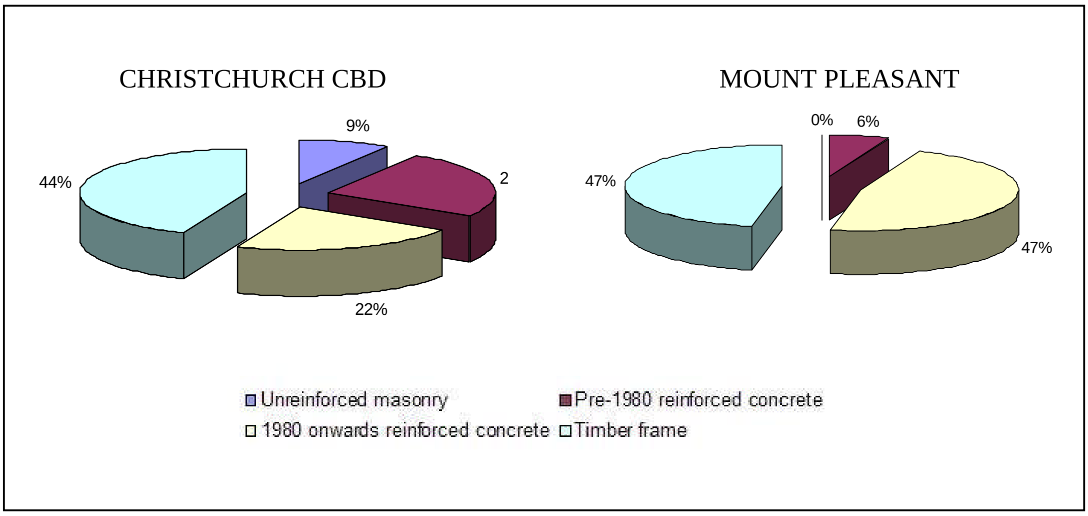

Figure 7.3 Estimated proportions of building construction types in the Christchurch CBD and Mt Pleasant.

Furthermore, the difference in the estimated amounts of loss observed between the two study areas could possibly be attributed to differences in site conditions. Differences in site conditions can cause quite dramatic variations in the hazard and consequently risk in the study region (Dhu & Jones, 2002). The Christchurch CBD is known to be located on soft soils whereas Mount Pleasant is situated in an area of mostly shallow soils (Brown & Weeber, 1992). Damage to buildings is highest where the ground comprises soft alluvial soils. This type of ground will experience increased ground shaking (amplification) and greater susceptibility to settlement or slumping from soil liquefaction, all of which will increase the building damage (Davey & Sheppard, 1995). It is important to note, however, that in a scenario 1 earthquake, the effects of liquefaction might not be very significant due to the lower intensity of shaking. Cousins (2005a) states that at intensities of MM6 to MM7 the effects of liquefaction are nearly always small and rarely cause significant damage. At higher intensities, MM8 and above, ground damage (settlement, spreading or displacement) often occurs and can result in substantial damage to buildings.

7.2.1 SPATIAL DISTRIBUTION OF BUILDING DAMAGE AND ECONOMIC LOSS

Of key interest to this study are the spatial variation of damage and loss in the two study areas and a determination of which areas are the most vulnerable when either of these two events occur. Figures 7.4 to 7.7 show maps of the spatial distribution of the average damage ratios depicting the relative vulnerabilities of the meshblocks. An average damage ratio for a meshblock is calculated by dividing the total economic loss in a meshblock by the estimated total replacement value of all buildings for that meshblock. Both maps in Figures 7.4 and 7.5 exhibit similar spatial patterns of vulnerability. For scenario 1, the average damage ratios range from 0.24 percent to 0.35 percent and for scenario 2, average damage ratios range from 1.52 percent to 1.87 percent. Meshblocks along the banks of the Avon River are generally the most vulnerable with localised meshblocks on the NE and west of the study area being the least vulnerable.

Figure 7.6 and 7.7 show maps of the spatial distribution of the relative vulnerabilities of the meshblocks in Mount Pleasant. Unlike the CBD, Mount Pleasant exhibits a clearly defined pattern of the relative vulnerabilities of the meshblocks due to both earthquake scenarios. There are large homogeneous areas indicating that these meshblocks and hence the buildings within them have similar vulnerability. For Scenario 1, the average damage ratios range from 0 to 0.13 percent. For Scenario 2, average damage ratios range from 0.15 percent to 0.72 percent.

Figure 7.8 and 7.9 show the distribution of economic loss suffered by both building classes in the Christchurch CBD, aggregated at meshblock level. A visual inspection of the two maps shows clearly that they both exhibit similar spatial patterns in terms of the distribution of loss. In both maps, meshblocks with greatest amounts of loss are generally clustered in the centre and towards the SE of the study area. These correspond to areas of highest building floor area and replacement value. Another interesting observation that can be made is that meshblocks on either side of the Avon River exhibit quite different amounts of loss. Meshblocks on the Hagley Park end of the River have generally lower losses than those on the opposite side. Once again, this is a function of higher building floor areas and replacement values. In a scenario 1 earthquake more than half of the CBD will sustain losses exceeding $100,000 with three

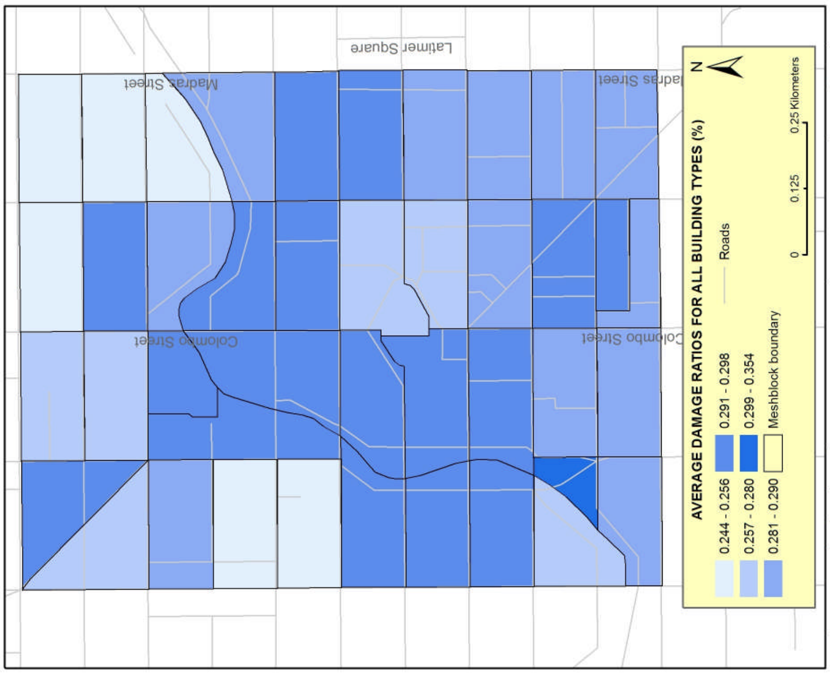

Figure 7.4 Distribution of average damage ratios by meshblock in the CBD in a scenario 1 earthquake.

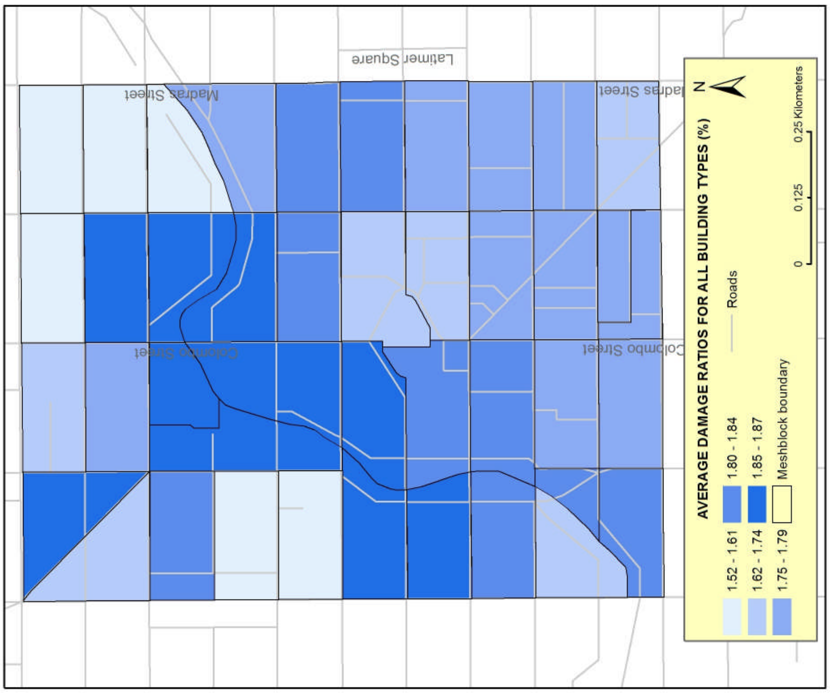

Figure 7.5 Distribution of average damage ratios by meshblock in the CBD in a scenario 2 earthquake.

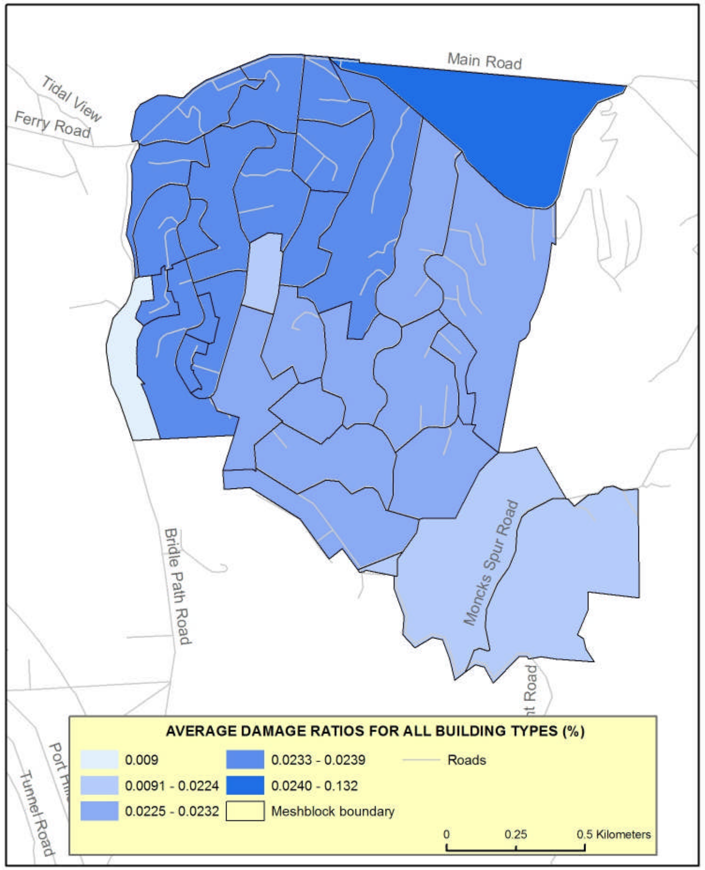

Figure 7.6 Distribution of average damage ratios by meshblock in Mt Pleasant in a scenario 1 earthquake.

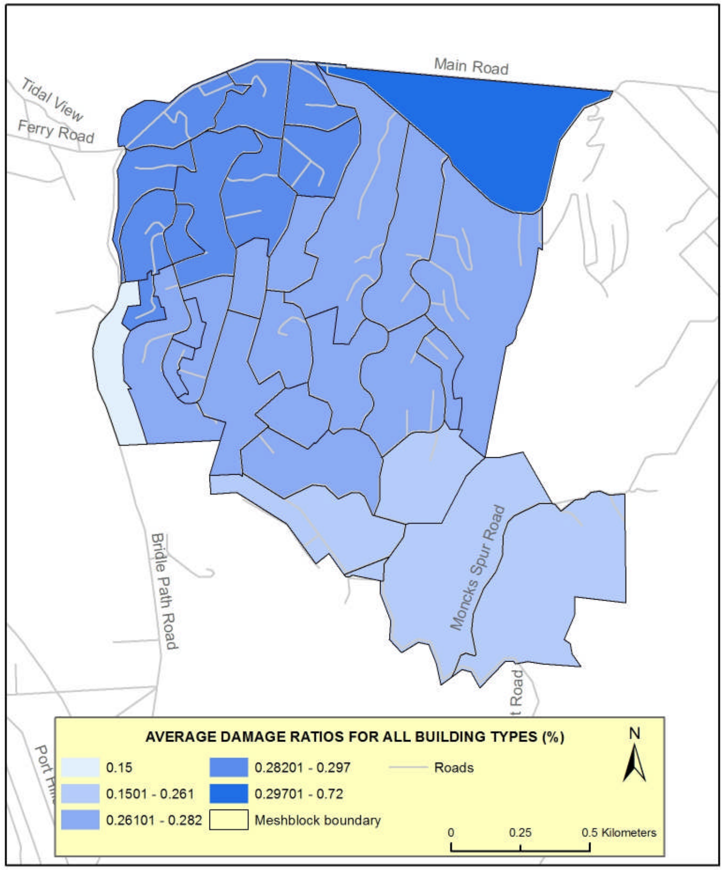

Figure 7.7 Distribution of average damage ratios by meshblock in Mt Pleasant in a scenario 2 earthquake.

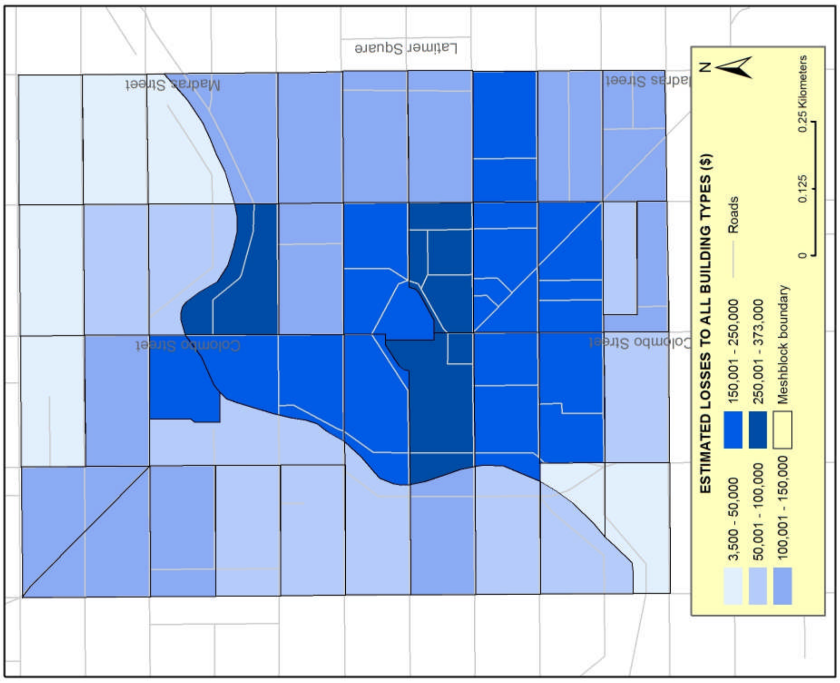

Figure 7.8 Distribution of total economic losses to all building types by meshblock in the CBD in a scenario 1 earthquake.

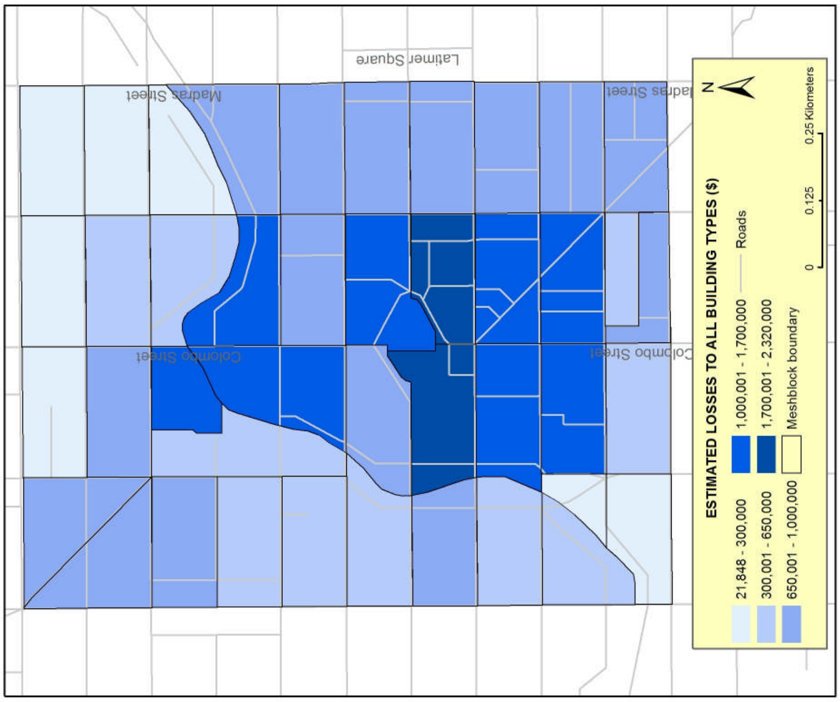

Figure 7.9 Distribution of total economic losses to all building types by meshblock in the CBD in a scenario 2 earthquake.

meshblocks in particular suffering losses in excess of $250,000. In the case of a scenario 2 earthquake (Figure 7.9), several meshblocks will sustain losses exceeding $1 million. Therefore, the maps clearly demonstrate that economic loss varies spatially across the study region.

Figure 7.10 and 7.11 illustrate the distribution of economic loss in Mount Pleasant aggregated at meshblock level. Once again, the maps further demonstrate that losses vary spatially across the study region. In neither of the two scenarios, is there a distinct pattern in spatial variation of loss, although meshblocks suffering the highest amounts of loss are generally clustered towards the centre of the study region. This is a function of higher building floor areas and replacement values.

7.2.2 PRECISION OF LOSS ESTIMATES

The economic loss estimates obtained in this study for a scenario 2 earthquake are considered reasonable and are probably within a factor of 2 to 3 of reality. The estimated intensities in Christchurch and Mount Pleasant from a scenario 2 earthquake are near MM8. Cousins (2004) has demonstrated that with this model it is possible to achieve a precision of about a factor of 2 to 3 when estimating losses from moderate to large earthquakes (magnitude 7 and above, giving intensities of at least MM8 in cities) affecting significant urban areas. However, when the prevailing intensity is MM7 or lower, as is the case in scenario 1, the uncertainty in loss estimates can possibly be up to a factor of 10 (Cousins, J. pers. comm. 2006). The loss estimates obtained for scenario 1, are still considered reasonable, although somewhat low, because this study is predicting loss for just small numbers of buildings and a very small area, that is, half of the CBD (1km by 1.2km) and the suburb of Mt Pleasant only. In addition, a qualitative

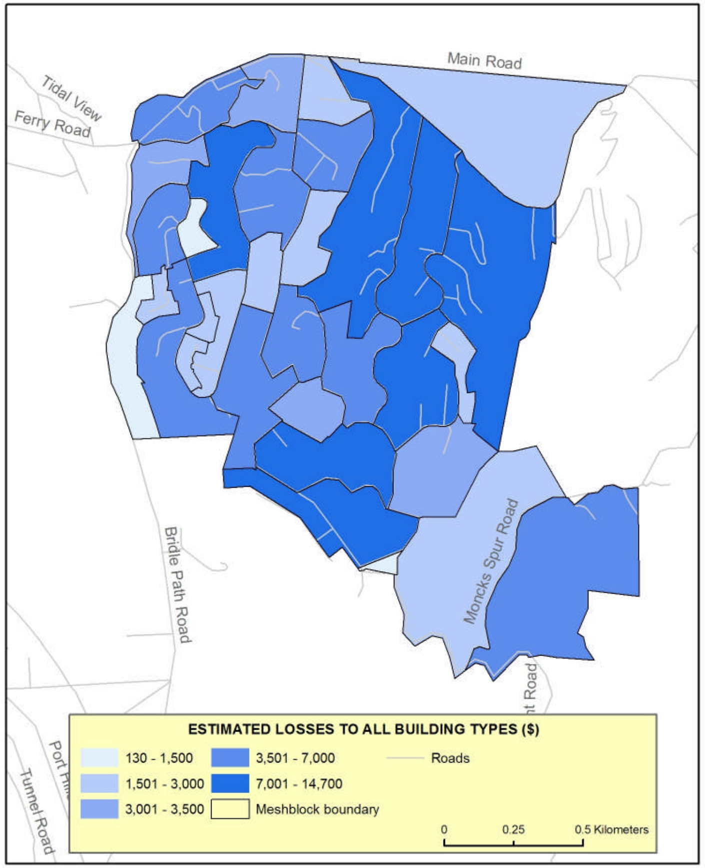

Figure 7.10 Distribution of total economic losses to all building types by meshblock in Mt Pleasant in a scenario 1 earthquake.

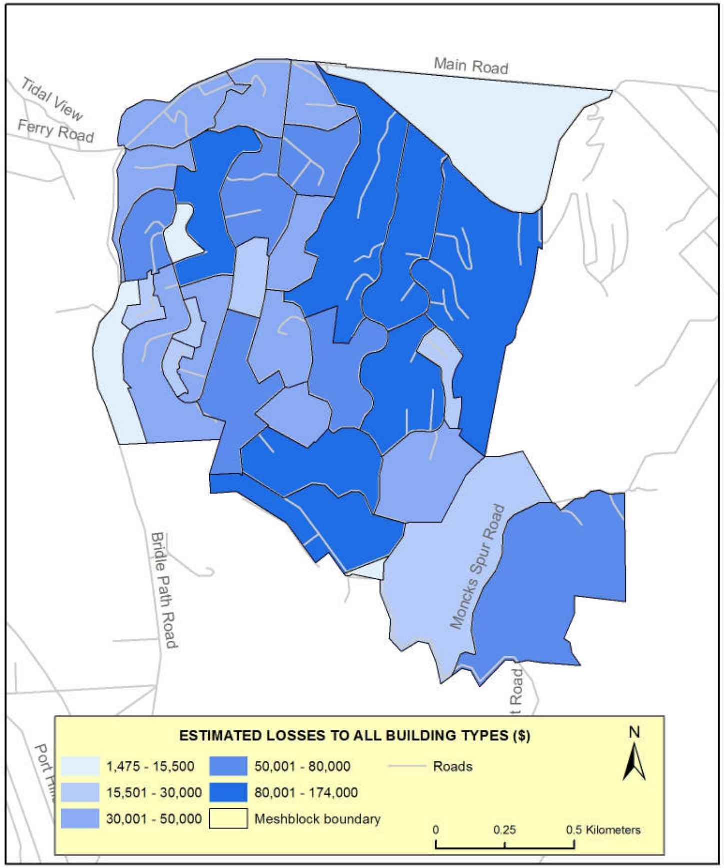

Figure 7.11 Distribution of total economic losses to all building types by meshblock in Mt Pleasant in a scenario 2 earthquake.

study by Elder *et al*.(1991b) (Table 7.3) suggests that at intensities of MM7 only some property damage is expected in Christchurch. It is important to note that a variability of a factor of 10 in loss estimates only applies when individual scenarios are modelled. Uncertainties in loss modelling are discussed in the next chapter.

7.3 CASUALTIES

In this study, the estimated numbers of casualties in a scenario 1 or scenario 2 earthquake are between 0 and 10. This is based on an estimated population distribution of approximately 22,700 and 3,120 in the CBD and approximately 1,750 and 5,550 in Mount Pleasant at daytime and night-time respectively. The estimated intensities in Christchurch and Mount Pleasant from a scenario 1 earthquake are MM7 and MM8 for a scenario 2 earthquake. It can be seen from Tables 7.3 and 7.4 that there is no risk of casualties at the MM7 zone and zero to low probability at the MM8 zone. Therefore, the findings of this study are considered reasonable.

Table 7.3 Approximate expected effect for various intensities of shaking in Christchurch (Elder *et al.,* 1991b).

MMI	Approximate Expected Effect	Average Return Period
6	Minimal property damage	7 years
7	Some property damage, loss of life unlikely	20 years
8	Significant property damage, loss of life possible	55 years
9	Extensive property damage, some loss of life	300 years
10	Catastrophic property damage, major loss of life	In excess of 6,000 years

Table 7.4 Death rates with their 95 percent confidence intervals associated with different types of structure in New Zealand, 1840-2003 (Dowrick & Rhoades, 2005).

	Deaths per head of population in or near structure			Deaths per structure		
	Mean	95% confidence interval limits		Mean	95% confidence interval limits	
MM8						
houses	0	0	1.9×10^{-5}	0	0	4×10^{-5}
non-domestic	0	0	3.1×10^{-4}	0	0	0.0013
URM	3×10^{-4}	1.5×10^{-5}	0.0016	0.0012	5.9×10^{-5}	0.0059
chimneys	0	0	2×10^{-5}	0	0	3.2×10^{-5}
MM9						
houses	0	0	1.1×10^{-4}	0	0	2×10^{-4}
non-domestic	0	0	5.5×10^{-4}	0	0	0.0035
URM	0.0056	0.0023	0.012	0.060	0.024	0.13
chimneys	3×10^{-5}	3.8×10^{-6}	3.6×10^{-4}	2×10^{-4}	5.7×10^{-6}	5.7×10^{-4}
MM10						
houses	0	0	1.6×10^{-4}	0	0	3.2×10^{-4}
non-domestic	0.0011	5.3×10^{-4}	0.0022	0.011	0.0052	0.021
URM	0.054	0.047	0.061	0.54	0.47	0.61
chimneys	3.9×10^{-4}	1.6×10^{-4}	8.2×10^{-4}	4.0×10^{-4}	1.6×10^{-4}	8.2×10^{-4}

Table 7.5 gives a summary of the known deaths and hospitalised injured people as a function of MM intensity in New Zealand earthquakes in the period 1840-2003 inclusive. It can be seen that casualties occurred in 16 earthquakes, which is at an average rate of one casualty-causing earthquake per decade. The estimated total numbers of direct deaths and hospitalised injured are 297 and 640 respectively. An important feature of Table 7.5 is what it says about the vulnerability of people to death as a function of intensity. It can be seen that only 1 percent of casualties have occurred at intensity MM7, 4 percent at each of MM8 and MM9 and the overwhelming majority (91 percent) have occurred at MM10 (Dowrick & Rhoades, 2005).

Table 7.5 Numbers of deaths and hospitalised injured as a function of MM intensity in New Zealand earthquakes, 1840-2003 inclusive (indirect casualties are excluded) (Dowrick & Rhoades, 2005).

Local date		Time	M_w	MM7		MM8		MM9		MM10	
				DTH	INJ	DTH	INJ	DTH	INJ	DTH	INJ
1843	Jul 8	1645	7.5			2					
1848	Oct 17	1540	6?	3							
1855	Jan 23	2102	8.2		1	2		6$^{(3)}$	4?		
1882	(1)	Day	5-6			3$^{(2)}$					
1897	Dec 7	0240	6.5		1						
1901	Nov 15	0745	6.8					1			
1913	Apr 12	1912	5.6	1	0						
1914	Oct 6	0646	6.6			1					
1922	Dec 25	1503	6.4				1				
1929	Jun 16	1017	7.7			3	1	12			
1931	Feb 3	1047	7.8			2	18	5	8	254$^{(4)}$	574$^{(4)}$
1932	Sep 15	0125	6.8				3				
1934	Mar 5	2346	7.4		1						
1942	Jun 24	2316	7.1				2				
1968	May 23	0424	7.2							2$^{(5)}$	2$^{(5)}$
1987	Mar 2	1342	6.5						1		
Totals				**4**	**3**	**13**	**25**	**24**	**13**	**256$^{(6)}$**	**596$^{(6)}$**

Notes:
$^{(1)}$ Date & hour not known; $^{(2)}$ could have been MM8; $^{(3)}$ 5 to 7 deaths; $^{(4)}$ Includes 27 injured who died; $^{(5)}$ Includes one injured who died: $^{(6)}$ Includes 28 injured who died.

The geographical distribution of casualties (deaths and injuries) from Table 7.5 and the seismic zone factor contours are shown in Figure 7.12. It can be seen that 97 percent of the total 924 casualties have occurred in the North Island. It is important to note that this distribution is due to the majority of casualties to date having occurred in the 1931 Hawke's Bay earthquake. Furthermore, the highest hazard part of the country, the South Island, has not contributed to the casualties count, and Dowrick and Rhoades (2005) argue that it cannot contribute much in the foreseeable future because it is lightly populated.

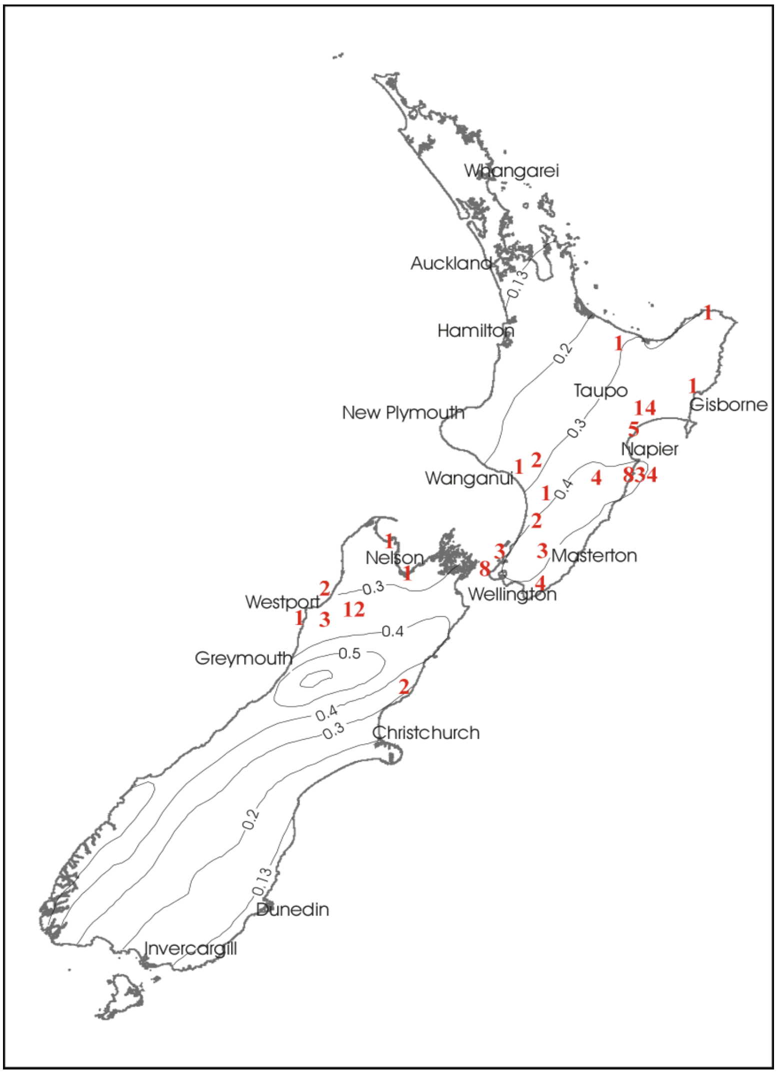

Figure 7.12 Geographical distributions of earthquake casualties in New Zealand in the period 1840-2001 inclusive. The numbers in red are the sums of deaths and hospitalised injured. Also shown are the seismic zone contours for the 500 year return period (from Dowrick and Rhoades, 2005).

Figure 7.13 shows the geographical distribution of deaths in the 1931 Hawke's Bay earthquake. It can be seen that all but, the two deaths in Wairoa lie within the MM9 isoseismal. Most of the deaths were in the Napier/Hastings area and were associated with an intensity of MM10. Hastings experienced a local intensity of MM10, although it lies outside the MM10 isoseismal. Furthermore, there were no reported injuries in the MM7 zone and approximately 4 percent were in the MM8 zone (Dowrick & Rhoades, 2005). It is important to note that the exposure in Hawke's Bay in terms of population was 30,000 during the 1931 event.

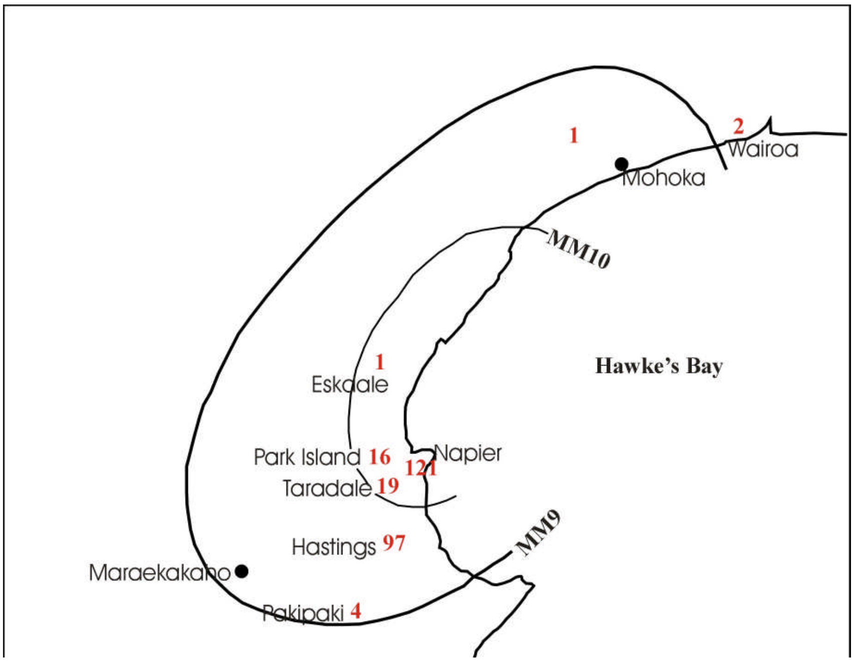

Figure 7.13 Geographical distributions of deaths caused by the 1931 Hawke's Bay earthquake, in relation to the intensity. Only two deaths occurred outside of the MM9 isoseismal (from Dowrick and Rhoades, 2005).

Tables 7.6 and 7.7 show the numbers of death and injured respectively and total population at risk due to building damage as a function of intensity. These data further demonstrate that in New Zealand earthquakes, casualty rates in the MM7 and MM8 zones are extremely low. The main type of construction responsible for causing deaths and injuries are unreinforced masonry and ureinforced masonry chimneys. It should be

Table 7.6 Numbers of deaths and total population at risk due to building damage as a function of Modified Mercalli intensity in New Zealand earthquakes (Dowrick & Rhoades, 2005).

Local date		Time	M_w	MM7		MM8		MM9		MM10	
				DTH	**POP**	**DTH**	**POP**	**DTH**	**POP**	**DTH**	**POP**
1848	Oct 17	1540	6?	3B							
1855	Jan 23	2102	8.2					4-6			
								Cob			
1901	Nov 16	0745	6.8					1 BC	5000		
1913	Apr 12	1912	5.6	1P	9300			1 Cob	200		
1931	Feb 3	1047	7.8			1B				6 BC	30,000
						1WT				240 B	
										8 NH	
Totals				**3B**		**1B**		**5-7 Cob**		**6BC**	
						1WT		**1BC**		**240 B** **8NH**	

Notes: B = URM; BC = Brittle chimney; Cob = Cob house; NH = Nurses home; P = Ornamental plaster; WT = domestic water tank.

Table 7.7 Numbers of injured and total population at risk due to building damage as a function of Modified Mercalli intensity in New Zealand earthquakes (Dowrick & Rhoades, 2005).

Local date		Time	M_w	MM7		MM8		MM9		MM10	
				INJ	POP	INJ	POP	INJ	POP	INJ	POP
1855	Jan 23	2102	8.2	1B	2,500			1 Wh	4,000		
								2 B			
								1BC			
1897	Dec 7	0240	6.5	1BC	11,000						
1922	Dec 25	1503	6.4			1BC	2,300				
1929	Jun 16	1017	7.7			1 BC	43,000				
1931	Feb 3	1047	7.8			18 B	28,000	8B	9,000	580 B	30,000
										6 BC	
										8NH	
1932	Sep 15	0125	6.8			2 UB	25,900				
						1B					
1934	Mar 5	2346	7.4	1 BC	6,000						
1942	Jun 24	2316	7.1			2 E	24,000	1 NS	11,000		
1987	Mar 2	1342	6.5								
Totals				**3**		**25**		**13**		**594**	

Notes: B = Bricks; BC = Brittle chimneys; NH = Nurses Home; E = Equipment; NS = Non- structure; UB = Unknown but probably brick; Wh = Whare (Maori house).

noted that there are significantly lower numbers of unreinforced masonry construction in New Zealand now, compared to the period between 1848 and 1942, which is when most of the casualties in the MM7 and MM8 zones occurred. This could possibly imply that if any of these events were to occur today, the expected numbers of casualties would be much less. Furthermore, application of this casualty model to some large historical earthquakes by Cousins (2004) shows that it performs quite well. Estimates of casualties are in line with that published by Dowrick and Rhoades (2003), except in three cases as follows: (1) the model's estimates are too low for deaths in the Buller earthquake of 1929 and injuries in the Wairoa earthquake of 1932; and (2) the model's estimates are too high for injuries in the Wairarapa earthquake of 1942 (Cousins, 2004). These are attributed to the following reasons:

1) All but one death in the Buller earthquake were due to landslides and rockfalls. The reason that this model under-predicts the deaths due to the Buller earthquake is because the nature of the lethal phenomena was quite small-scale relative to the widely spaced data points used in the model for the sparsely populated area near the Buller earthquake. Given these reasons, the under-prediction by the loss model is unavoidable;

2) In the model, single data points are used to represent the small population centres that were affected by the Wairoa and Wairarapa earthquakes. In cases where one data point is predominant, the casualty estimates derived from the model are highly sensitive to the distance from the epicentre of the earthquake to that data point. The effect of increasing the distance of the epicentre to the data point results in a decrease in the number of casualties. Furthermore, the

historical death associated with the Wairarapa earthquake that occurred in Wellington was due to gas poisoning. The loss model would not have predicted this.

3) Two sets of results are reported for the Hawke's Bay earthquake. One is based on the building types of 1931 Napier and the other on modern buildings types. In 1931, 44 percent of the commercial buildings in Napier were of unreinforced masonry. This was reduced to an assumed 1 percent in 2004. This resulted in significantly reduced numbers of casualties.

It is obvious from the above discussion that loss modelling estimates fall into error intervals because of various and very different factors. Several factors that influence loss estimates are discussed in the next chapter.

7.4 SUMMARY

The results of this study suggest that the total combined direct economic loss due to building damage in the Christchurch CBD and Mount Pleasant will possibly be in the order of $5.6 million and $35.3 million in a scenario 1 and scenario 2 earthquake respectively. These values have been calculated in 2005 dollars on the basis of the total replacement value of buildings in the two study areas, which was estimated by this model to be approximately $2.5 billion. Damage to non-residential buildings constitutes the vast majority of the economic loss. There is spatial variation in the distribution of economic loss at meshblock level in both the study areas. Finally, in either scenario, the casualty numbers are expected to be between 0 and 10. There is definitely higher probability of casualties in the CBD for daytime earthquakes than for the same event at night-time. For Mount Pleasant, on the other hand, there is higher probability of casualties at night because more people are there at night than during the day.

CHAPTER 8

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 INTRODUCTION

The main objective of this study was to assess the seismic risk to the buildings and population in the Christchurch CBD and Mount Pleasant due to two hypothetical earthquake events. It uses a methodology that is comprehensible and appropriate for achieving such an analysis. The results of this research indicate that characteristics and magnitude of risk resulting from building damage in the Christchurch CBD and Mount Pleasant due to the two earthquake scenarios are not random, but are a function of the spatial variation of the earthquake hazard, the elements at risk, and the vulnerability of the elements at risk to the hazard. In this chapter a summary of the main findings of this research are presented, followed by a discussion on the inherent uncertainties in seismic risk assessment studies. Finally, the main conclusions of this research and recommendations for future work are given.

8.2 SUMMARY

This study illustrates the characteristics and magnitude of risk resulting from building damage in the Christchurch CBD and Mount Pleasant due to two earthquake scenarios: (1) a magnitude 8.0 earthquake on the Alpine fault, at a distance of 130km from

Christchurch, which produces shaking intensities of near MM7 in the city and (2) a magnitude 7.0 earthquake on the Ashley fault, at a distance of 25 km from Christchurch that produces shaking intensities of near MM8 in the city. The primary hazard considered was earthquake ground shaking. This deterministic assessment incorporates several component models as follows: (1) an attenuation model for earthquake shaking; (2) building inventory; (3) population distribution; (4) building damage; (5) building collapse; (6) economic loss; and (7) casualty rates. A GIS served as a platform for collecting, storing and analyzing the original and the derived data.

Results of this study suggest that the total combined direct economic loss due to building damage in the Christchurch CBD and Mount Pleasant will possibly be in the order of $5.6 million and $35.3 million in a scenario 1 and scenario 2 earthquake respectively. These values have been calculated in 2005 dollars on the basis of the total replacement value of buildings in the two study areas, which was estimated by this model to be approximately $2.5 billion. Of special importance is the high amount of damage and loss incurred by the non-residential buildings in the CBD. This is mainly attributed to two factors: (1) the presence of a significant number of unreinforced masonry and pre-1980 reinforced concrete buildings in the CBD and (2) the presence of soft alluvial soils in the CBD. There is spatial variation in the distribution of damage and economic loss at meshblock level in both the study areas. Meshblocks exhibiting higher losses generally correspond to meshblocks of higher building floor areas and replacement values. The estimated number of casualties in a scenario 1 or scenario 2 earthquake is between 0 and 10. This is based on an estimated population distribution of approximately 22,700 and 3,120 in the CBD and approximately 1,750 and 5,550 in Mount Pleasant at daytime and night-time respectively. There is definitely higher probability of casualties in the CBD for daytime earthquakes than for the same event at night-time. For Mount Pleasant, on the other hand, there is higher probability of casualties at night because more people are there at night than during the day.

Furthermore, findings of this study leads to knowledge/awareness of the possible extent of damage and loss, which the two study areas could possibly sustain, if the scenario earthquakes were to occur. In addition, by utilizing GIS technology, this research attempts to improve upon our understanding of the geographic variation of seismic risk in Christchurch due to building damage caused by earthquake ground shaking. A GIS not only provides the analytical “engine” for the risk assessment, it also provides a potent form of risk communication through its capacity to provide a visual representation of the spatial distribution of seismic risk in the city.

8.3 UNCERTAINTIES IN SEISMIC RISK ASSESSMENT STUDIES

The natural variability of earthquake-related processes means that there are many uncertainties in hazard and loss estimation processes (Cousins, 2005a). In this seismic risk assessment study, several assumptions and approximations were involved which consequently influence the outcomes in terms of estimated damage and loss for a given locality. The following sections describe the uncertainties associated with the component models used in this seismic risk assessment study.

8.3.1 DETERMINISTIC vs PROBABILISTIC METHODOLOGIES

In this study, a deterministic seismic risk assessment methodology was used and the assessment of risk is based on damage and loss calculated to result from the occurrence of two hypothetical earthquakes. As explained in earlier chapters, in a deterministic approach, single-valued events or models are used. That is, an earthquake of a certain size on a specific seismic source, occurring at a certain distance from the area of concern. A disadvantage of this approach is that it does not take into account the inherent uncertainty in seismic hazard estimation (Reiter, 1990). Another weakness is that frequency of occurrence is not explicitly taken into account.

In a probabilistic approach, uncertainties in the earthquake occurrence and ground motion estimation process are explicitly considered (Reiter, 1990). Site ground conditions are estimated for selected values of the probability of ground motion exceedance in a design time period or for selected values of annual frequency or return period for ground motion exceedance. The hazard maps (and the risk maps on which they are based) are usually presented in terms of a given return period. For example, ground motions could be estimated for a 10 percent probability of exceedance in 100 years or for a return period of 950 years.

The disadvantages of a probabilistic approach are that vast quantities of data, theory and judgement must be included, integrated and processed to reach the final hazard analysis. This has the tendency to obscure the basic causative factors of the hazard often leading to false impressions of accuracy (Reiter, 1990). Furthermore, there is no unique result for the relationship between ground motion level and probability of exceedance. Probabilistic seismic hazard results show large uncertainty bands, sensitivity to outliers, and large differences between central estimates such as the median and the mean, thus placing a heavy burden on those who have to use the results (Reiter, 1990).

It is obvious from the above discussion that deterministic and probabilistic methods both have their advantages and disadvantages. Therefore, it is the end use of the analysis that should decide what methodology is adopted (Mualchin, 2004). A deterministic approach was considered ideal for this study because it is a clear and concise way of assessing seismic risk and it provides prompt and meaningful results which can be easily understood by people from a wide range of backgrounds.

8.3.2 UNCERTAINTIES DUE TO FAULT RUPTURE LENGTH, MAGNITUDE, DISTANCE AND FAULT MECHANISM

1. RUPTURE LENGTH

Even though the two earthquake scenarios utilised in this study were based on sound geological and seismological data, they still have sources of uncertainty as mentioned above. For example, in scenario 1, there are uncertainties regarding what part of the Alpine fault will rupture and to what extent. Seismologists are not sure how much of the Alpine fault will rupture in any given earthquake. Therefore, Milford-Haupiri (Segment 4) was chosen because it is the longest single rupture, with Segment 4 simply placing the epicentre in the northernmost of four possible segments of the rupture (Cousins, pers comm.2005). This is likely to give worst-case intensities of shaking in Christchurch.

2. MAGNITUDE

The uncertainty in magnitude is often given as ±0.3. In this loss model the result of change in magnitude can be profound as can be seen in Figure 8.1, although the sensitivity of the damage ratio to change in magnitude appears to depend mostly on the intensity at the location of interest and is independent of the starting magnitude (Cousins, 2005b).

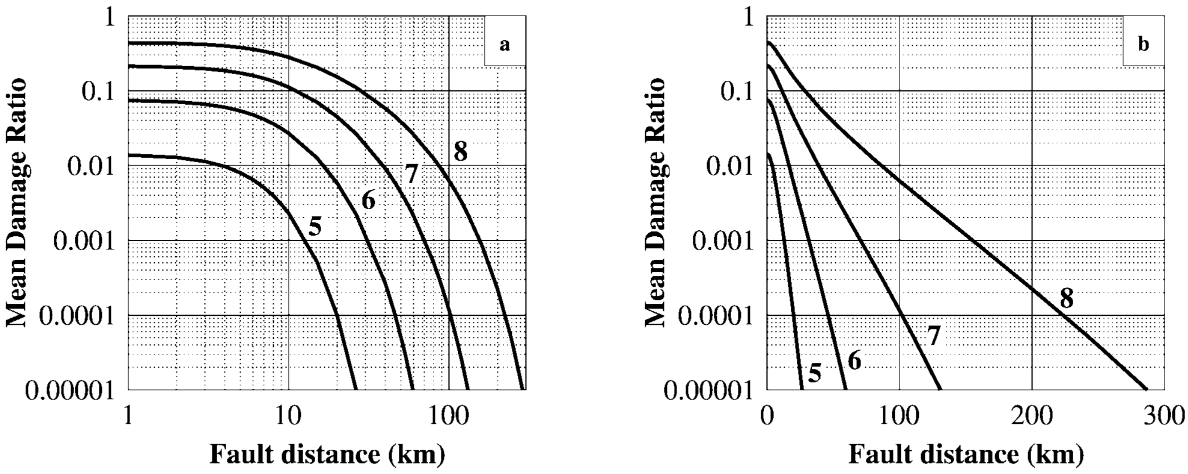

Figure 8.1 Attenuation of damage ratio for average New Zealand houses, for earthquakes of magnitude 5, 6, 7 and 8. Plot (a) shows that there is relatively little decrease in damage ratio within the first few km from source, while plot (b) shows that at larger distances there is almost a linear relationship between log(Dr) and distance (Cousins, 2005b).

3. DISTANCE

A further observation from Figure 8.1, is that, in the near source (that is within 5km) the change in damage ratio with distance is relatively small and does not change greatly with magnitude but in the far-field, where the intensity is about MM6 and the damage ratio is about 0.0001, the sensitivity to distance is larger than near-source and increases with decreasing magnitude (Cousins, 2005b). Examples of the factorial increases in damage ratio for 5km decreases in distance are given in Table 8.1

Table 8.1 Factor by which damage ratio increases in response to a 5km decrease in source-site distance, for various sizes of earthquake and various distances from source (Cousins, 2005b).

Magnitude	5	6	7	8
Factor – near source	1.8	1.4	1.2	1.17
Factor – far field	6.0	2.3	1.5	1.19

4. FAULT MECHANISM

Altering the fault mechanism of an earthquake produces changes in damage ratio similar to those arising from alterations in magnitude. When the intensity is high, MM9 or greater, the factorial change in damage ratio due to a change in mechanism from normal to strike-slip is less than 1.4. At intensity MM6 the factor is 20, and at MM5 it is 70,000 (Cousins, 2005b).

Finally, Cousins (2005b) argues that for individual scenarios, as were employed in this study, the above uncertainties alone can give rise to uncertainty factors of 2 to 3 for earthquakes of large magnitudes and high intensities, increasing to factors of 10 (or more) for earthquakes of small magnitudes and low intensities. The larger the earthquake, the less the details influence the overall outcome of the loss modelling but for small earthquakes, the results can depend critically on the above factors. However, Cousins (2005b) has shown that it is possible to achieve loss estimates within a factor of 2 for all cases with this model by averaging the results of many thousands of scenarios and by varying the input parameters from one scenario to another.

8.3.3 ATTENUATION OF GROUND SHAKING

There are several models of attenuation of ground shaking (Dowrick & Rhoades, 1999; McVerry *et al.*, 2000) for New Zealand and these models give rise to different predictions. Attenuation relationships are used to convert earthquake magnitude to local ground shaking parameters and there is a high degree of uncertainty associated with them (Melchers, 1991). The Dowrick and Rhoades (1999) model of attenuation of ground shaking is the most appropriate for this study because it is the most recent MMI model for New Zealand. Unlike McVerry *et al*. (2000), Dowrick and Rhoades (1999) used the MM intensity, rather than peak ground acceleration (PGA) or spectral acceleration, because damage ratio data are collected and analysed for intensity zones (i.e. MM7, 8, etc) so they can be applied only in terms of MM intensity. Furthermore, the common practice of first calculating PGA, then converting it to MMI, is fraught with difficulty because of the high frequency content of PGA from small earthquakes at short distances (Smith, 2003). At high frequencies the PGA may be high but the effect on buildings is small. Dowrick and Rhoades (1999) have provided a function which estimates MM intensity directly, and is reported by Smith (2003) to be the best tool for the purpose of using the damage ratio information.

8.3.4 SITE EFFECTS

While intensity attenuation equations give damage distribution as regional trends, it is well known that these are frequently subject to very significant local deviations as a result of topography and soil. Local conditions might increase the intensity by one or two degrees, with significant impact on the final damage and loss estimates. This has been witnessed in several earthquake events in Mexico City in the years 1957, 1979 and 1985 (Rojahn, 1994) and in San Francisco in 1906 and 1989 (Erdik, 1998). Microzoning maps need to be based on more information than that on surface geology maps, and the required extra criteria (such as engineering properties of the soil) need to be better understood (Dowrick & Rhoades, 2003) to remove this source of uncertainty.

8.3.5 BUILDING INVENTORY

The predictions of damage and loss depend not only on the parameters that are used in the damage and loss models, but also on the building inventory database that has been used. While the building inventory that was used in this modelling is a reasonably good reflection of the composition of building construction types and usages in the two study areas, the Christchurch City Council property valuation database that was used to compile the building inventory was not perfect. First, it did not contain any data on building replacement values, building heights or load-bearing elements and contained very limited data on building age. These data sets are vital for damage and loss modelling and were therefore estimated based on several assumptions. Errors in assumptions will perturb the estimates of building damage and loss calculations. Furthermore, one of the most important uncertainties is in the assumed proportion of unreinforced masonry construction in the Christchurch CBD building stock, because unreinforced masonry buildings contribute heavily to earthquake damage and losses. Any changes in the proportions of building construction types will result in changes in the estimated damages and losses.

8.3.6 POPULATION DISTRIBUTION MODEL

The assumptions and approximations used to determine the distribution of the population in the two study areas are manifold. The census data is not designed for use in earthquake loss modelling. A significant weakness is the lack of daytime information. Hence, considerable judgement was necessary in organising available census information. Furthermore, building occupancy is rather variable; hence it is practically impossible to produce a model that predicts where a population will be at given time (Aggett, 1994).

8.3.7 DAMAGE AND LOSS MODEL

The most significant factor influencing the degree of loss calculated in a seismic risk assessment study is the damage ratios used to define the vulnerability of the elements at risk (Aggett, 1994). Damage ratios for the classes of buildings considered in this study are based largely on cost and value data gathered from just a few earthquakes and any misjudgement of the building fragilities could be a significant source of error. Furthermore, in this study, the buildings are aggregated into categories based on construction type and usage and the seismic performance of these categories are generalised. Even though mean damage ratios which are appropriate for aggregated data are used in this study, it is unrealistic to believe that every timber-framed building in the study area will suffer the same amount of damage given a certain level of ground shaking. Also, knowing only the mean level of damage is inadequate because serious injuries and casualties are usually related to extreme damage experienced by a minority of buildings (FEMA, 1989).

8.4 CONCLUSIONS

This study demonstrates a methodology for earthquake risk assessment. The main focus of the study was on estimation of direct economic loss and casualties due to building damage caused by earthquake ground shaking in two earthquake scenarios. Findings are based on:

- Data describing the earthquake ground shaking and microzonation effects;
- An inventory of buildings by floor area, replacement value and occupancy;
- Damage ratios, defining the performance of buildings as a function of earthquake intensity;
- Daytime and night-time population distribution data; and
- Casualty functions defining casualty risk as a function of building damage.

The main findings of this study are as follows:

- The Christchurch CBD and Mount Pleasant will suffer an estimated total economic loss of around $5.6 million in a scenario 1 earthquake and $35.3 million in a scenario 2 earthquake. Given the significant rise in property values and growth in development that has occurred in Christchurch, these numbers perhaps underestimate the amount of replacement dollars that would be needed to rebuild in the two areas of concern should there be a significant seismic event;
- The estimated number of casualties in a scenario 1 or scenario 2 earthquake is between 0 and 10. This result was considered reliable based on comparisons with historical records of earthquake-related deaths and injuries in New Zealand. There is definitely higher probability of casualties in the CBD for daytime earthquakes than for the same event at night-time. For Mount Pleasant, on the other hand, there is higher probability of casualties at night because more people are there at night than during the day;
- The results clearly demonstrate that risk varies spatially across the study areas and that majority of the loss will be incurred due to damage to non-residential buildings in the CBD. This is of concern because the CBD contains many of the critical facilities and have significant concentrations of people during the day. The variation in risk can be attributed to differences in the underlying geology in the two study areas and differences in construction types in the building stock;

The results of this study are dependent upon the accuracy and appropriateness of both the data collected and the models used. Further refinement of the models may change some of these results; however, they are a good indicator of the nature of earthquake risk in Christchurch and Mount Pleasant due to building damage.

8.5 RECOMMENDATIONS

- This seismic risk assessment methodology assesses direct economic loss and casualties due to building damage caused by ground shaking only. The scope of this methodology can be expanded to take into account losses from secondary effects such as fire following earthquakes, landslides, tsunami, etc. Furthermore, this methodology has not addressed the direct economic losses from business interruption or indirect losses. An assessment of these losses would give a more complete estimate of the total risk due to earthquakes in the two study areas. In addition, the impact on the broader community due to impaired lifeline functioning such as electric power and water supply needs to be investigated. A study by the Christchurch Engineering Lifelines Group (1997) has assessed the vulnerability of lifelines in Christchurch to natural hazards. The socio-economic implications of earthquake impacts also need to be assessed. In the first instance, the simplest socio-economic vulnerability models would relate structural damage to the impact on all community activities and the time taken to restore the community to its normal state. Geological and Nuclear Sciences (GNS Science) has assembled some relevant information for Wellington to develop socio-economic loss models for earthquake events (Cousins & Heron, 2000). Similar studies should be carried out for Christchurch;

- Information on actual exposure of buildings is very important. Efforts need to be put into developing systematic approaches to preparing building inventories in terms of earthquake vulnerability classes, which can then be used in seismic risk estimation studies or for other purposes, for example, in estimating the vulnerability of the buildings to other hazards such as fire and wind. This information would also be valuable to the insurance industry;

- The effects of microzoning need to be checked, modified and models produced as necessary to make them appropriate for the various soil types in Christchurch. This requires a long term engineering research effort. Improved definition of ground classes and their amplification factors need to be developed;

- The potential for very high losses to result from liquefaction makes ground damage a major issue for Christchurch. Work by Park *et al* (1994), indicates that the greatest influence on liquefaction is the water table. A recent study done by Beca Carter Hollings & Ferner (2004) for Environment Canterbury provides ground damage maps for two groundwater levels, and indicate high, moderate or low liquefaction potential due to an earthquake on the Alpine fault;

- The damage and loss models can be further reviewed by the structural engineering community to improve confidence in the results produced by them;

- The results of this risk assessment are useful to assess overall trends. They can be factored into future planning decisions from the point of view of determining the most effective measures that can be taken to minimise the likely economic losses when an earthquake occurs;

- Cousins (2005b) has performed a sensitivity analysis on the model to determine whether changes in inputs such as earthquake magnitude, distance and the fault mechanism cause significant changes in damage and economic loss estimates.

The results of the sensitivity analysis point to areas where efforts should be made to improve the models or collect new data. Reduced variability in the models will lead to more accurate and reliable estimates of risk;

- The purpose of this study was to estimate direct economic loss and casualties due to building damage caused by earthquake ground shaking. Although the focus of this research has been on earthquake ground shaking, the methodology can be easily applied to other natural and man-made hazards such as hurricanes, flooding and hazardous material accidents;

- The use of GIS creates better opportunities for data visualisation and rapid evaluation of alternative scenarios. GIS enabled this research to achieve more detailed and analytically sophisticated results than have previously been possible. The increased ability to visualise data allows for a better understanding of spatial patterns that might not have otherwise been apparent;

- Although damaging earthquakes are rare in Christchurch, the high impact of individual events on the community makes them a costly natural hazard. With increasing urbanisation and dependence on power, water, telecommunications and other lifelines, the communities in Christchurch are becoming more vulnerable to earthquakes and an analysis such as this is useful for indicating areas that have the potential for large damage and loss in future events;

- Improved awareness by the political decision makers, as well as the general public, of the utility of a GIS-based seismic risk analysis cannot help but improve the hazard mitigation and emergency response efforts in Christchurch.

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APPENDIX

Appendix 1

Modified Mercalli (MM) Scale

(adopted from USGS webpage URL: http://neic.usgs.gov/neis/general/mercalli.html)

The following is an abbreviated description of the 12 levels of Modified Mercalli intensity.

I. Not felt except by a very few under especially favourable conditions.

II. Felt only by a few persons at rest, especially on upper floors of buildings.

III. Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.

IV. Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.

VI. Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.

VII. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.

VIII. Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

XI. Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.

XII. Damage total. Lines of sight and level are distorted. Objects thrown into the air.